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Current and Advanced NO_x-Control Technology for Coal-Fired Industrial Boilers

prepared by

KVB, Inc.

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COAL UTILIZATION PROGRAM

ARGONNE NATIONAL LABORATORY

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CURRENT AND ADVANCED NO_x-CONTROL TECHNOLOGY FOR COAL-FIRED INDUSTRIAL BOILERS

Prepared by

KVB, Inc.
Tustin, California

for

Argonne National Laboratory

December 1978

Work sponsored by
Division of Environmental Control Technology
Assistant Secretary for Environment
United States Department of Energy

FOREWORD

This report is one of a series issuing from the Environmental Control/ Coal Utilization Program at Argonne National Laboratory. It is the first of the series to deal with industrial installations. The program is sponsored by the Division of Environmental Control Technology, Assistant Secretary for Environment, U.S. Department of Energy. The primary objectives of the program are the characterization and assessment of available and emerging environmental-control technologies for coal-based power generation.

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CURRENT AND ADVANCED NO_x-CONTROL TECHNOLOGY FOR COAL-FIRED INDUSTRIAL BOILERS

ABSTRACT

A NOx-control-technology assessment study of coal-fired industrial boilers was conducted to examine the effectiveness of combustion-modification methods, including low excess air, staged combustion, and burner modifications. Boiler types considered included overfed and underfed stokers, spreader stokers, pulverized-coal and coal-fired cyclone units. Significant variations in NOx emissions occur with boiler type, firing method, and coal type; a relative comparison of emission-control performance, cost, and operational considerations is presented for each method.

Baseline (as-found) emissions from grate-fired stokers were shown to be in the range of 200 to 300 ppm. Similarly, as-found emissions from suspension-fired units were quite low (350 to 600 ppm) as compared to comparably designed utility-sized units. Low excess air was shown to be the most effective method on existing units, reducing emissions by approximately 10%. Evaluation of staged combustion and burner modification, however, were limited due to current boiler designs. Major hardware modification/design and implementation are necessary before the potential of these techniques can be fully evaluated.

The study emphasized the numerous operational factors that are of major importance to the user in selecting and implementing a combustion-modification program, including energy considerations, incremental capital and operating costs, corrosion, secondary pollutants, and retrofit potential.

1 INTRODUCTION

The Department of Energy has recognized the importance of expanded coal use in meeting future energy needs and achieving the long-term goal of national energy independence. The electrical-utility industry has reverted to coal for much of its power generation, and industry is once again ordering more coal-fired industrial boilers for process steam generation than oil- or gas-fired units. However, environmental restrictions play an important role in the increased use of coal. Future emissions regulations of 100 to 200 ppm of NOx for coal-fired utility boilers are a distinct possibility, and similar regulations are possible for industrial boilers. The South Coast Air Quality Management District (SCAQMD) in Los Angeles, California, is considering regulations that would require a 50-90% reduction in NOx emissions from most industrial boilers firing principally oil and gas fuel. Although it is uncertain whether other districts and states will follow the California example, the Combustion Research Branch of EPA and the Office of Air Quality Performance Standards (OAQPS) have been concerned about NOx emissions from industrial boilers. Research programs to examine potential NOx-control methods have been conducted for more than two years, and OAQPS is now considering possible NOx standards for industrial boilers.

The industrial- and utility-boiler NOx emissions are a significant fraction of the total stationary-source emissions. Increased pressures for reduced emission levels are expected, since further reductions in the automotive sector have for the moment reached a technological impasse. NOx is one of the remaining major or criteria pollutants that has not been effectively reduced to levels approaching 10% or less of an uncontrolled source.

Expanded use of coal fuel could be a detriment to air quality, since coal fuel is comparatively high in fuel-nitrogen content, and the control of fuel-nitrogen conversion is a difficult problem in reducing NOx emissions. Certain NOx-control techniques that were very effective on natural gas and light oils are relatively ineffective on coal fuel, because the majority of the NO originates from the oxidation of the fuel-bound nitrogen rather than from thermal fixation of nitrogen and oxygen in the combustion air. In recent years, techniques to reduce NOx emissions on coal-fired utility boilers have been developed, but frequently these methods are not conveniently applied to smaller industrial boilers, which include a large fraction of stoker units. For the reasons outlined above, a need existed to examine NOx-control technology as specifically applied to industrial boilers.

1.1 PURPOSE AND OBJECTIVES OF THE PROGRAM

The objective of this study is to provide an assessment of the effectiveness and applicability of conventional NOx-control technologies appropriate for coal-fired industrial boilers. An associated objective is to identify unresolved issues, information gaps, and needed R&D efforts pertaining to the development of advanced NOx-control techniques. It should be emphasized that this study is concerned primarily with the conventional combustion of coal. Advanced combustion concepts will not be excluded, but prior assessment studies have covered emissions and operational aspects of fluidized-bed combustion, solvent-refined coal, beneficiated coal, and low-Btu gasification/combined-cycle combustion.

The current assessment study of conventional-combustion NOx-control technology was performed for Argonne National Laboratory as part of an on-going program, *Environmental Control Implications of Coal Utilization for Power Generation,* which covers the other combustion processes previously mentioned. The objective of the overall Argonne program is to provide comparative technical, environmental, and economic assessments of emission-control technologies for processes used in the generation of electricity from coal. This information will in turn be provided to the DOE Office of the Assistant Secretary for Environment for use in their program-planning efforts. Although industrial boilers are frequently used for process steam generation, it should be noted that many of the largest industrial boilers (and largest NOx emitters) are used for in-plant electrical generation. This trend is expected to continue with the spreading of co-generation and co-siting total-energy-management industrial-park developments.

It should be noted that this assessment study is not restricted just to the control efficiency of various combustion-modification methods for NOx control. Capital and operating costs as well as operational factors associated with the implementation of a combustion-modification technique are also important. The review of problems in design, installation, operation, and maintenance of combustion-modification techniques comprises an important section in this final report. Although these operational considerations are examined from the user's viewpoint rather than from a strict regulatory perspective, they are critical factors in the overall accomplishment of a desired emission-compliance effort. For example, if potential problems of corrosion, erosion, combustion stability, energy penalties, retrofit potential, secondary pollutants, incremental capital and operating costs, etc., are not fully addressed in the development and implementation of a control method, then the user will be unable to provide effectively the desired emission level, regardless of the control effectiveness demonstrated previously at the R&D stage. For these and other reasons outlined previously, it was desirable to conduct a detailed assessment of NOx-control methods that was specific to coal-fired industrial boilers. The general approach to the study is very similar to that followed in a prior NOx-control-technology assessment for coal-fired utility boilers (Ref. 1-1).

1.2 ORGANIZATION OF THE FINAL REPORT

The previous section has summarized the program objectives and general program philosophy, but several comments concerning the structure of the final report are appropriate before initiating the technical discussion. The report has been divided into three general levels of interest or intended readership. The summary in Section 2 was intended for the management-level reader interested primarily in a synopsis of program objectives, approach, and principal conclusions from the final report. (This section was also prepared so as to be of interest to the non-technical reader or to the technical reader working outside of his specialty but interested in a brief overview of the subject.)

The main body of the report (Sections 3 - 7) is directed at a technical readership and should also be of interest to other investigators working in the field. Each of the major report sections has been written as a standalone section with separate references, etc., so that a reader interested only in a specific topic area could appreciate the content of that section without having read the rest of the report.

Section 3 is a general introductory discussion of coal-fired industrial-boiler design types, sizes, applications, coal usage, and NOx emissions. Subsections discuss in more detail the NOx-emission characteristics of cyclone, wall-fired, tangentially-fired, and vertically-fired pulverized-coal-burning units, as well as stoker units. The discussion of stoker designs covers underfed, overfed, and several types of spreader stokers. Although this discussion will be of benefit primarily to those readers not intimately familiar with industrial-boiler design configurations, the discussion of uncontrolled or "baseline" NOx emissions should be of interest to all readers, since it forms the basis for subsequent comparisons of reduced-NOx modified-combustion operating modes.

Section 4 is a detailed assessment of combustion-modification techniques for NOx control and represents one of the major elements in the study. The principles of operation of each control method, such as low-excess-air (LEA) operation and staged combustion, are discussed, followed by examples of NOx emissions control on each boiler type. The general technique of staged combustion can be implemented by biased firing, by burners-out-of-service operation, and through the use of overfire-air ports; data useful for comparing these methods are presented for applicable boiler types. A summary of NOx-reduction potential and costs associated with various combustion-modification techniques is provided in Sections 4.5 and 5.4 (The discussions in Section 4 are organized by boiler type and then by control technique so that a reader interested in a specific boiler type and a given control method should be able to conveniently locate the desired section in the table of contents.)

Section 5 is one of the more important sections of the report from the user's viewpoint, since it concerns operational considerations in implementing combustion-modification techniques as discussed in Section 4. This review covers five major topic areas:

- Problems in design, installations, operation, and maintenance of a NOx-control technique
- Applicability of a NOx-control technique for retrofit

- Possible energy penalties associated with the implementation of a given NOx-control method
- Impact of low-NOx modes on other pollutants
- Effect of the control technique on the performance of auxiliary equipment

Since the potential problem of water-tube-wall corrosion, slagging, and fouling is a concern in some low-NOx modes, a discussion of this topic area is presented in Section 5.1.5.

Section 6 examines the emissions and operational factors to be considered in switching from high-sulfur eastern to low-sulfur western coal. Although the reduced sulfur emissions are evident, the impact on NOx emissions and boiler operating characteristics, particularly with stoker units, has not been widely publicized. A section on chemical additives (7) follows for those readers interested in their applicability for corrosion control, combustion alteration, and equipment-efficiency improvement.

Sections 8 and 9 discuss several advanced concepts for NOx control and R&D needs to satisfy future emissions goals in the industrial-boiler sector. Because of the revival of the stoker for industrial applications with the return to coal, a large portion of this discussion centers on needs in stoker-technology development. Unresolved issues and future information needs that prevented a complete assessment in some topic areas are summarized at the end of the report.

REFERENCES FOR SECTION 1

1-1 *Assessment of NOx-Control Technology for Coal-Fired Utility Boilers*, ANL/ECT-3, Appendix D (December 1977).

2 *SUMMARY*

2.1 *INTRODUCTION*

Emissions from stationary combustion sources have been effectively controlled to 10% or less of their initial levels for all major or criteria pollutants except NOx. The conversion of fuel-bound nitrogen to NO during the combustion process makes the control of NOx emissions from coal-fired boilers particularly difficult. However, coal is our largest natural fossil-fuel resource, and DOE is responsible for developing methods of utilizing coal in an environmentally acceptable manner. Coal is used extensively for power generation by the electrical-utility industry, but the increased use of coal in industrial applications can not be ignored, particularly in air-quality-control regions where NOx air-quality standards are barely being met or are exceeded. Consistent with its responsibilities, EPA has established research goals for NOx emissions from coal combustion of 200 ppm by 1980 and 100 ppm by 1985. EPA is also currently assembling background technical-support documentation for a yet-to-be-proposed industrial-boiler NOx-emissions regulation.

For the reasons outlined above, a need existed to conduct a comprehensive state-of-the-art review of all potential combustion-modification methods for NOx control on coal-fired industrial boilers. Combustion modification has in the past been the most cost-effective approach to limiting NOx formation and emissions. With the resurgence of interest in spreader-stoker units, it was desirable to document the most recent technical developments, as well as longer-term R&D needs, associated with that boiler-design category.

2.2 *IMPORTANCE OF STATIONARY-SOURCE NOx AND COAL-FIRED INDUSTRIAL-BOILER EMISSIONS*

A number of developments have occurred in the last few years that have significantly altered the relative importance of NOx, possible options for NOx control, and relative cost-effectiveness of these options. Stationary-source NOx emissions have become subject to increasing pressure by the regulatory agencies as prime candidates for more restrictive emission regulations. Some of the developments that have led to this significant change in emphasis in recent years include:

- relaxation or postponement of the NOx-emission standards for light-duty vehicles
- re-evaluation of ambient-NO_2 concentrations (using chemiluminescent analyzers) indicating that many more air-quality-control regions may be in violation of national air-quality standards than previously projected
- the successful development of new low-NOx burners for pulverized-coal units that have operated with emission levels of less than 0.4 lb/MBtu
- the complete combustion of coal in laboratory-scale experiments with less than 200 ppm final NO, demonstrating that methods exist to overcome fuel-nitrogen conversion
- the demonstration of a method for selective gas-phase destruction of NO at the laboratory scale that holds promise for stack-gas-treatment systems that will not create associated waste-disposal problems

The recent trend toward more stringent stationary-source NOx regulations is largely due to the combined effect of continuing air-quality needs and recent research progress towards significantly reduced emission levels. Either factor, lacking the other, probably would not be sufficient to substantiate new regulations, but together they provide a strong incentive to plan and evaluate NOx-control strategies that could be applied to coal-fired boilers.

2.3 NOx EMISSIONS FROM COAL-FIRED INDUSTRIAL BOILERS

NOx is formed during coal combustion from two sources: (1) the thermal fixation of atmospheric oxygen and nitrogen and (2) the conversion of fuel-bound nitrogen. The availability of oxygen, as well as temperatures over 3000 °F, contributes heavily to both thermal and fuel-derived NOx formation. The important parameters for both formation modes have been identified as local stoichiometry, temperature, mixing, and residence time at these conditions. Burner, grate, and furnace configurations are important factors in NOx formation, since they influence mixing patterns, heat release, and absorption rates as well as residence times within the furnace.

Significant variations in firing methods and combustion conditions occur in industrial-sized coal-fired boilers. The smaller units (up to approximately 250,000 lb/hr steam flow) are largely stoker-fired units. They differ primarily in the mechanical method of coal introduction into the furnace, including overfed, underfed, and spreader stokers. These units are characterized by release and combustion of volatile materials above the grate and bed combustion of the resulting char on the grate. In spreader stokers, the coal is hurled into the furnace so that devolatilization and some particle combustion occurs prior to landing on the grate. In all stokers, the bulk of the combustion air is supplied through the grate.

Larger boilers generally use suspension firing in pulverized-coal or cyclone units. In these units the combustion air is supplied with the coal through individual burners. Several configurations of pulverized-coal-fired units are used. These include tangential, single-wall, horizontally opposed, and vertically fired boilers. They differ primarily in the location, arrangement, and type of burners in the furnace. Apart from size and the corresponding number of burners, these boilers are similar in design to utility-sized units.

A summary of baseline (as-found) NOx-emission levels by boiler firing type is presented in Table 2-1. The stoker-fired units exhibit relatively low emission levels as compared with suspension-fired units. The variations in and

Table 2-1. Summary of Baseline NOx-Emission Levels

Firing Type	NOx Emissions, ppm (3% O_2 Dry) Current Program	Reference 2-2*
Suspension-Fired		
Cyclone	800	1200
Single Wall	350-900	750
Horizontally Opposed	500	750
Tangential	400-500	550
Vertical	---	550
Stoker		
Underfed	250-350	300
Overfed	200-300	475
Spreader	300-600	300

*After conversion from a lb/10^6-Btu basis to ppm.

among stokers and pulverized-coal combustion units are due to the differences in combustion intensity and oxygen availability in the primary combustor regions. The NOx-emission levels from pulverized-coal-fired boilers are within the ranges of emissions for small, comparably fired utility boilers (Ref. 2-1).

Also presented in Table 2-1 is a comparison of these NOx-emission levels with values from previous assessment programs(Ref. 2-2). With the exceptions of horizontally opposed and cyclone units (both of which showed wide ranges in emissions, as discussed in Ref. 2-1) and overfed stokers, the emission levels compare very favorably.

2.4 COMBUSTION MODIFICATIONS TO REDUCE NOx EMISSIONS

Combustion modifications, including low-excess-air and staged combustion, have been used effectively to reduce baseline NOx-emissions concentrations. A summary of the NOx-reduction potential, expressed as the percent reduction in NOx from baseline conditions at comparable excess-O_2 levels, is presented in Table 2-2. This table is somewhat incomplete, due to the limited data available and the inappropriateness of some combustion modification to certain unit-type combinations.

Table 2-2. Summary of NOx-Reduction Potential

Firing Type	LEA	Air Register Adjustment	BOOS	Simulated OFA Injection Systems	Simulated OFA Aux. Burners	Bias
Suspension-Firing						
Cyclone	5%	-	-	-	-	-
Single Wall	5 to 10%	15%	30 to 45%	-	-	-
Tangential	10%	-	40%	-	-	12 to 25%
Stokers						
Underfed	10%	NA	NA	-	-	NA
Overfed	10%	NA	NA	0 to +20%	-	NA
Spreader	10 to 15%	NA	NA	0 to 5%	10 to 20%	NA

NA- Not Applicable

Low-excess-air combustion (LEA) involves operating the boiler with a reduced amount of overall excess air. Minimum excess-air levels are determined by unsatisfactory boiler-operating conditions with excessive carbon carryover.

Industrial boilers tend to be operated at various levels (0 to 5% excess O_2) above practical minimums, due to improper air or fuel distribution, instrument limitations, operator/maintenance neglect, etc. The reduction potentials presented in Table 2-2 apply to a one-percent reduction in excess-O_2 level. In many instances, the actual reduction potential of LEA (considering the larger available margin in excess O_2) was greater than the more complex staging techniques.

Staging the combustion process into primary and secondary combustion regions can be achieved through burner-out-of-service (BOOS) and overfire-air (OFA) operation. These techniques are very effective in reducing NOx emissions by reducing the availability of oxygen in the primary combustion zones. The application and reduction potential of these techniques are highly dependent on the location and flexibility of the unit's coal and air supply to the furnace.

BOOS is implemented by terminating the flow of coal to selected burners (and thereby increasing coal flow to the remaining burners) while maintaining air flow through all burners. In this manner, sufficient segregation of fuel-rich and air-rich zones is created to influence NOx formation. The reduction potential of BOOS is dependent on the degree of staging (percent of BOOS), which is severely limited on industrial-sized units by the small number of burners involved. Reduction potentials presented in Table 2-2 represent operation with 25% of the BOOS and reduced loads. These reduction potentials are comparable to the results from utility-sized units with the same degree of staging (Ref. 2-1). The widespread application of BOOS to industrial units is questionable, due to load restrictions, unless modifications to burner and coal-preparation systems are made.

OFA operation has been simulated on stoker units by means of existing overfire-air injection systems (installed for increased turbulence in the volatile combustion regions directly above the bed) and through the air-supply systems for auxiliary, wall-mounted burners. As given in Table 2-2, the use of overfire-air injection systems has been shown to have little effect on reducing NOx emissions and, in fact, increased emissions on an overfed stoker. Use of auxiliary burners, however, reduced NOx-emission levels by 10 to 20%. These data indicate that optimum design of OFA ports for NOx control could show significant reduction potentials on stoker units. Although data on an industrial-sized suspension-fired unit equipped with OFA ports were not available, the results from utility-boiler tests showed reduction potentials of 15% and 30% for single-wall and tangentially fired units, respectively.

The data presented in this section were compiled from field-test programs conducted by KVB under sponsorship of the EPA and DOE (Ref. 2-3, 4, 5, and 6). For the most part, the reduction potentials presented in Table 2-2 pertain to conditions at one load point for short-duration tests under steady operating conditions. Examination of these combustion modifications under fluctuating or reduced load conditions over extended periods must be made prior to their full implementation as routine operating procedures.

It should also be emphasized that there are large unit-to-unit variations in coal-fired industrial-boiler NOx emissions, even within the same boiler-design type. This is due to varied boiler geometry with size, age, and coal type. Boiler operating practice, maintenance, coal preparation, and coal-combustion characteristics often vary from plant to plant, even within the same region. Frequently a plant in the northeastern U.S. may obtain coal simultaneously from two or three sources. Therefore, it is not unusual to see baseline NOx emissions vary by as much as 400 ppm for a given boiler type. Because of this wide variation in baseline emissions, the reader is cautioned that the NOx-reduction potentials listed in Table 2-2 can not be guaranteed for <u>all</u> existing units <u>regardless</u> of boiler age, design, coal type, etc.

2.5 OPERATIONAL CONSIDERATIONS

The impact on boiler operations of the initial and long-term use of combustion modifications is, in many respects, as important as the associated NOx-reduction potential, when considering the use of these techniques. Application of procedures that would seriously affect the safety, reliability, or expected lifetime of these units would be considered unacceptable by boiler owners and operators. Although the implementation of staging techniques in industrial units has been applied only on a test basis, experiences from (1) utility units using BOOS and OFA as normal operating procedures and (2) industrial units operating with LEA for efficiency reasons can give insight into their possible initial and long-term impacts.

The question of corrosion of the water walls is usually the main concern when implementing LEA or staged combustion. The results of a long-term corrosion study for coal firing by the EPA will soon be available. In this study a staged-combustion mode was implemented over a six-month period. Tube sections were removed for physical comparison with normal baseline firing. Extensive ultrasonic mapping was also done before and after the low-

NOx tests. No long-term corrosion tests in low-NOx operating modes have been performed on industrial boilers, and therefore the EPA utility-boiler program is the only near-term source of corrosion results.

Initial considerations include those factors related to the implementation of the combustion-modification program. For an existing unit, the NOx-reduction program begins with a thorough maintenance check and necessary repairs to assure that the unit is in good operating condition, followed by evaluation tests of the combustion flexibility to establish optimum conditions for low-NOx emissions. Recommendations for the addition of auxiliary equipment for improved control of excess-air levels and unit modifications for improved staging capabilities may be made. Although modifications to industrial boilers have been limited to advanced combustion control for improved efficiency, the success of these techniques on utility units and under simulated test conditions certainly warrants further evaluation. Demonstration of their effectiveness may make such procedures an integral part of new industrial-boiler designs.

Possible increases in maintenance requirements, fuel usage, corrosion, and secondary pollutants are the major long-term concerns. While additional maintenance may be required, the resulting improvements in unit operation should compensate for this effort. Proper implementation need not result in increased fuel usage and may in fact improve operating efficiency. The effect on grate and tube-wall corrosion rates has not been determined and will require long-term tests under controlled conditions. Increased particulates, CO, and other pollutant emissions due to the combustion modifications are of great concern, especially with respect to the magnitude and character of particulates, which may alter the collection efficiency of particulate-control devices. Tests have shown that the levels of these pollutants were not increased and, in certain cases, even were reduced through proper implementation procedures.

Perhaps the most important operational concerns, from the standpoint of the owner/operator, are the initial and long-term costs involved. Use of LEA will generally result in a net savings due to reduced fuel usage. Advanced staging procedures, including hardware and auxiliary-equipment additions, are not anticipated to be severe, representing 0.1 to 0.3% of the total annual cost of operation (including annualized capital, fuel, and maintenance costs).

2.6 WESTERN-COAL NOx EMISSIONS

Most western subbituminous coals can be burned in industrial-size coal-burning equipment. The ease with which this fuel switch can be made depends on the furnace type. For pulverized-coal firing, the fuel switch means lower maximum continuous loads, due to excessive superheated-steam temperatures. Nitric-oxide emissions from pulverized-coal-fired boilers burning western coal were on the average 20% lower than those for eastern coal on the same units. This may be due to the lower peak flame temperatures of the high-moisture western coal. The western coals could be fired at lower excess air than the eastern coals before the smoke or combustible threshold was reached.

Stoker-fired boilers, like pulverized-coal-fired boilers, have high-superheat load limitations when firing the high-moisture western coals. In addition, many stoker designs, in particular the underfed and overfed stokers, could more easily fire western coals if better under-grate-air control were provided. NOx emissions from stokers burning western coal were on the average about 10% lower than eastern coal on the same units.

2.7 USEFULNESS OF CHEMICAL ADDITIVES

The use of additives in coal-fired boilers is not widespread. There is some information that indicates that MgO may be useful in controlling high-temperature slagging and fouling and the resultant fireside corrosion. The additives work by changing the composition of the ash such that the eutectic melting point is higher. This action inhibits slag formation. Once slag is formed, the magnesium component helps change the physical characteristics such that the deposits are more easily removed by sootblowing operations.

Cold-end additives are used for corrosion control. Again, MgO is recommended to remove SO_3 from the flue gas and lower the acid dewpoint.

No information was obtained on the use of combustion-improvement additives in coal-fired systems. However, oil-fired boilers sometimes use an additive formulated from barium to increase the smoke limit to lower excess air. Recent tests in our laboratory demonstrated the usefulness of an additive in reducing smoke emissions from a staged SRC flame.

2.8 *ADVANCED CONCEPTS FOR NOx CONTROL FROM COAL-FIRED INDUSTRIAL BOILERS WITH RECOMMENDATIONS FOR FURTHER RD&D EFFORTS*

Advanced staged-combustion-modification concepts for pulverized-coal flames seem to have the most promise for control of NOx emissions. Such staging techniques utilize the divided chamber as well as the aerodynamically controlled low-NOx burner. Early indications from the divided-chamber work are very promising. Stack NOx emissions under 100 ppm have been achieved at the 4,000,000-Btu/hr scale on four different coal types.

Advanced NOx-control concepts for stokers revolve around the use of overfire air coupled with good under-grate-air management to reduce the overall bed excess air and to lower NOx emissions. No research is currently under way on fuel-bed NOx-formation processes.

REFERENCES FOR SECTION 2

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2-2 Mason, H. B., et al., *Preliminary Environmental Assessment of the Application of Combustion-Modification Technology to Control Pollutant Emissions from Major Stationary Sources*, EPA Contract 68-02-2160 (March 1977).

2-3 Cato, G. A., et al., *Field Testing: Application of Combustion Modifications to Control Pollutant Emissions from Industrial Boilers - Phase I*, EPA 650/2-74-078a (October 1974).

2-4 Cato, G. A., et al., *Field Testing: Application of Combustion Modifications to Control Pollutant Emissions from Industrial Boilers - Phase II*, EPA 600/2-76-086a (April 1976).

2-5 Maloney, K. L., et al., *Systems Evaluation of the Use of Low-Sulfur Western Coal in Existing Small- and Intermediate-Sized Boilers*, EPA 600/7-78-153A, July 1978.

2-6 Gabrielson, J. E., et al., *A Testing Program to Update Equipment Specifications and Design Criteria for Stoker-Fired Boilers*, EPA/DOE Contract EF-77-C-01-2609 (unpublished information).

3 BASELINE NOx-EMISSION LEVELS FROM COAL-FIRED INDUSTRIAL BOILERS

As a class, industrial boilers exhibit a wide variety of firing methods and boiler types ranging from small mass fed stoker units for steam production to large pulverized coal units for in plant electrical generation. Industrial size boilers are generally considered to be in the size range from 10,000 lb/hr to 500,000 lb/hr steam flow. According to their actual application, as shown in Fig. 3-1, the industrial boiler category overlaps both the utility size at the higher capacities and commercial boilers at the low design capacities. The low capacity industrial boilers exhibit the characteristics of commercial boilers, whose auxiliary equipment and combustion control systems may be limited, while the large size industrial boilers resemble sophisticated utility boiler systems.

Besides boiler steam capacity, other variables in categorizing industrial boilers are major differences in basic boiler configuration and firing method. Industrial size boilers include both firetube and watertube units. Firetube boilers are generally limited to ∿ 30,000 lb steam/hr and occupy the low end of the industrial boiler size spectrum (Ref. 3-3). Firetube units consume 5.4% of the total coal input and produce 4.1% of the total NOx attributed to industrial boilers (Ref. 3-2). Although the watertube boiler population declines below 30,000 lb steam/hr where firetube boilers begin to predominate, coal firing in firetube units is not standard practice due to ash fouling problems. For the purposes of this report, the boilers discussed will be only of the watertube variety. This restriction is due not only to the relative low NOx emission and coal usage of firetube boilers, but also to the availability of field test data in these units.

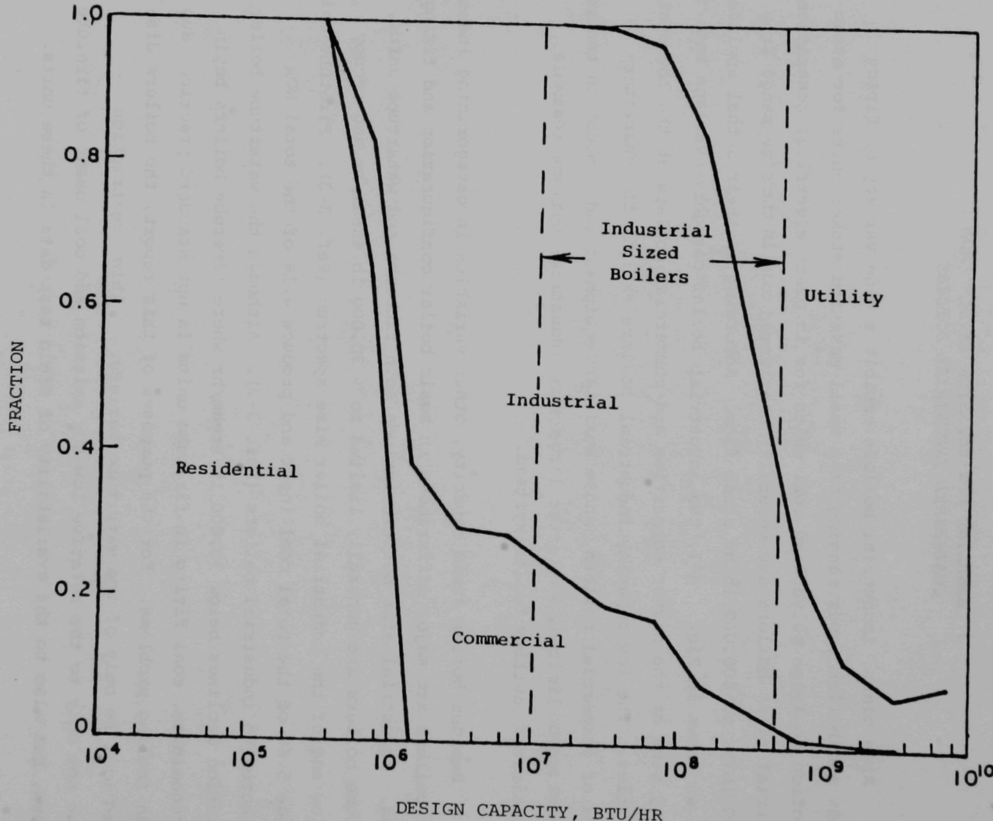


Fig. 3-1. Boiler use related to boiler size (Ref. 3-1).

The category of watertube industrial boilers includes a great variety of coal firing methods and boiler types. A major difference in firing method is the distinction between pulverized coal and stoker-fired units. Unlike the utility size boilers, which are almost exclusively pulverized coal (or crushed coal in the case of cyclone fired units), the capacity range of industrial boilers is represented by large numbers of both firing methods.

Considering the number of stoker manufacturers and the number of boiler companies serving the industrial boiler market and the changes in design philosophy which have taken place over the years since stokers were first introduced around 1900, it is not surprising that the present stoker-fired boiler population represents a highly individualized array of equipment. A similar situation exists regarding pulverized coal-fired boilers. Since their commercial inception in 1920, many changes in furnace shape, burner design, amount of furnace water cooling, method of ash removal, and heat release rate have evolved, so that units tend to be highly individualized and tailored to the expected coal characteristics and plant requirements.

Above approximately 250,000 lb/hr steam flow, almost all boilers employ pulverized coal firing. These large boilers closely resemble utility boiler designs and generally differ only in steam capacity. Boiler types include single wall fired, tangentially fired, cyclone, vertically and horizontally opposed units. In general, the NOx characteristics of each boiler type are similar to those found in utility boilers. The manner in which the NOx emissions differ from comparable utility boilers and the limitations in implementing NOx control measures that size imposes are major elements of this report.

Between 100-250,000 lb/hr steam flow, the existing boiler population shows a mixture of pulverized coal firing and stoker-fired units. Below 100,000 lb/hr steam flow, the stoker-fired units predominate. Stoker-fired boilers, as a class, differ greatly in their methods of coal injection, combustion and ash removal. As a result, NOx control techniques which are generally well characterized for pulverized coal firing cannot be easily extrapolated to stoker-fired units. In all stokers the bulk of the combustion process occurs in a bed of coal and ash, with the combustion air fed from below the bed rather than the suspended particle combustion characteristic of pulverized units.

The major categories of stoker types include spreader stokers, underfed stokers and overfed stokers, which identify the differences in the manner of coal injection into the boiler. The methods of operation of these stoker systems will be discussed in more detail in later sections. Additional stoker subcategories or types distinguish the method of ash removal from the bed surface or grate. The grate types include traveling or chain grate, vibrating grate and dumping grate.

Existing field test data characterizing the NOx emissions from industrial boilers are not nearly so extensive as the data available for utility size boilers. This is attributable to the research allocations being in relative proportion to the contribution of a source type to total NOx emissions. The net result is a general lack of NOx emission data for many of the categories of industrial boilers. This problem will become more apparent in the later sections where combustion modification for the reduction of NOx is discussed.

Estimates of the total coal usage and NOx emissions from coal-fired industrial boilers are presented in Table 3-1. These data (although dated as 1972, they represent the most recent fuel use data for industrial units) show that stoker units are predominant both in terms of fuel usage and NOx emissions.

Table 3-1. Estimates of Coal Use and NOx Emissions[a] From Industrial Watertube Boilers for 1972

	Coal Usage		NOx Emissions	
Pulverized-Coal-Fired	10^{12} Btu/Yr	%	10^3 TPy	%
Tangential	80.0	4.8	30	6.1
Horizontally Opposed	28.8	1.7	12	2.4
Single Wall	52.8	3.2	21	4.3
Vertical	5.3	0.3	2	0.4
Cyclone	35.0	2.1	28	5.7
(Subtotal)	(201.9)	(12.1)	(93)	(18.9)
Stoker Fired				
Spreader	641.2	38.3	179	36.2
Underfed	567.7	34.0	144	29.1
Overfed	169.6	10.1	53	10.7
Not Classified	91.2	5.5	25	5.1
(Subtotal)	(1469.7)	(87.9)	(401)	(81.1)
Total	1671.6		494	

[a]Reference 3-2.

3.1 SUMMARY OF BASELINE NOx-EMISSION LEVELS

The baseline NOx emission levels for the various categories of coal-fired industrial boilers discussed in the following sections are summarized in Table 3-2. In most instances, these estimates are based on a limited number of field test results. As discussed, coal-fired industrial boiler operation represents a large number of units with a wide variety of boiler and fuel types. The levels presented in Table 3-2 should, therefore, be taken as representative only.

As given in Table 3-2, stoker-fired units characterized by bed combustion on a grate exhibit relatively low NOx emission levels, generally in the range of 200 to 300 ppm. Suspension fired units including spreader stokers and pulverized-coal-fired units, have higher emission levels.

Table 3-2. Summary of Baseline NOx-Emission Levels

Firing Type	NOx Emissions, ppm (3% O_2 Dry) Current Program	Reference 1-2[a]
Suspension Fired		
Cyclone	800	1200
Single Wall	350-900	750
Horizontally Opposed	500	750
Tangential	400-500	550
Vertical	---	550
Stoker		
Underfed	250-350	300
Overfed	200-300	475
Spreader	300-600	300

[a]Converted from a lb/10^6 Btu basis to ppm.

The difference between these emissions is due to the formation mechanisms of NOx in the combustion process. NOx is formed by both the thermal fixation of atmospheric oxygen and nitrogen and the conversion of fuel nitrogen. It is believed that the NOx formed in grate combustion systems comes primarily from the conversion of fuel nitrogen. NOx formed during suspension firing, on the other hand, includes both mechanisms under combustion conditions promoting higher NOx emission levels. While the formation mechanisms for coal-fired units are not well understood, several important parameters have been identified including local stoichiometries, temperature, mixing, and residence time. Burner, grate and furnace configurations are important factors in NOx formation since they influence mixing patterns, heat release and absorption rate and residence time.

Also presented in Table 3-2 is a comparison of these emission levels with accepted values from previous assessment programs (Ref. 3-22). With a few exceptions, notably to unit types with wide ranges in emissions, these emission levels compare very favorably.

3.2 *ORGANIZATION OF NOx-EMISSION-TEST DATA*

Test data for utility boilers can frequently be identified according to the generating station name and the unit number. This is generally not the case for industrial sized boiler test data where the test site and occasionally some equipment details are anonymous. For example, one major source of data is based upon a location and test number system. In another source, the boilers are identified solely by type (e.g. stoker) which is not sufficiently detailed for this assessment where it is desirable to categorize the NOx emissions by stoker type.

For convenience in data analysis for this study, certain boiler tests have been redesignated according to an arbitrary IB- numbering system. Table 3-3 presents these new identifiers and the boiler and test numbers they represent in the original report. The IB- identification system will be utilized throughout this report and is provided for cross reference purposes.

Table 3-3. Boiler Index

I.D. Number	Original I.D.	Reference
IB-1	Location 11, Test 18	3-6,3-8
IB-2	Location 12, Test 26,75	3-6,3-8
IB-3	Location 12, Test 77,78	3-6,3-8
IB-5	Location 13, Test 31,156-159	3-6,3-7,3-8
IB-6	Location 14, Test 27	3-6,3-8
IB-7	Location 14, Test 28	3-6,3-8
IB-8	Location 15, Test 16	3-6,3-8
IB-9	Location 15, Test 17	3-6,3-8
IB-10	Location 20, Test 32	3-6,3-8
IB-11	Location 21, Test 19	3-6,3-8
IB-12	Location 21, Test 20	3-6,3-8
IB-13	Location 30, Test 134-139	3-7,3-8
IB-14	Location 31, Test 131-133,169	3-7,3-8
IB-15	Location 35, Test 165-168	3-7,3-8
IB-16	Stoker boiler	3-5
IB-17	Horizontal opposed fired boiler	3-5
IB-18	Location 22, Test 42	3-6,3-8
IB-19	Location 22, Test 43	3-6,3-8

A summary table of all NOx related testing on industrial sized boilers is presented in Table 3-4, giving the boiler type, available emission test results and coal characteristics.

3.3 PULVERIZED-COAL-FIRED BOILERS

Pulverized-coal-fired boilers are generally restricted to the large steam capacities above approximately 100,000 lb/hr steam, due to the cost of the fuel preparation system required for operation. While pulverized coal fired systems are universally used in utility boilers, they are not dominant in industrial use. As given in Table 3-1, pulverized coal boilers consume only approximately 12% of the coal used in the industrial sector (Ref. 3-4). However, 18.9% of the NOx emitted from coal-fired industrial boilers is attributed to them (Ref.3-2). This is due to the higher emission rates for pulverized coal boilers. The rates for cyclone fired and wet bottom pulverized coal furnaces are even higher. Emission rates range from 0.75 to 1.25 lb/MBtu for pulverized coal compared to 0.417 to 0.625 lb/MBtu for stoker units (Ref. 3-2). This difference is generally attributable to the characteristically high intensity of combustion employed in pulverized coal units.

Since the only major difference between industrial size pulverized coal units and utility boilers is capacity, the same type of burners, if not identical ones, is used in the industrial units. Where a utility boiler may have as many as 60 burners, an industrial unit is generally restricted to a few, in accordance with the required capacity.

All of the available pulverized coal-fired industrial boiler NOx emission data for baseline or unmodified operation is presented in Fig. 3-2. It is evident that there is a general scarcity of data in this particular class. Unfortunately, there are too few data to establish the general NOx characteristics as a function of boiler capacity. In two cases, the horizontally opposed and the cyclone boilers, only one baseline test was reported in the literature.

Table 3-4. Industrial-Boiler NOx-Test-Data Summary

	Boiler Type								Test Type										Coal Analysis								
													Staged														
Unit	Ref. (3-)	Blr. Type	# Burners/ Stokers	Capacity (10^3 lb/hr)	Mfg.	Area (10^3 ft^3)	Vol. (10^3 ft^3)	Grate Type	Base	Load	LEA	Stkr. Air Reg. Adjmt.	BIAS	BOOS	OFA	CO	Part.	Misc.	Type	HHV	%C	%H	%N	%S	%O	%H_2O	%Ash
IB-5	6,7, 8	SW	6	500	B&W	7.3	34.9		X	X	X								E	12.3	69.9	4.7	1.5	1.4	8.1	3.4	14.5
IB-14	7,8	SW	4	260	CE	5.0	19.5		X	X	X			X					E	12.3	68.3	4.7	1.5	1.2	11.0	3.4	9.7
IB-17	5	HO		150					X	X									E	13.2	72.2	5.0	1.6	2.3	9.2	2.0	7.7
Alma #3	9	SW	4	230			15.0		X	X	X			X		X	X	a,b	E	10.8	59.9	4.2	1.1	3.7	9.7	7.5	14.5
Fremont #6	9	SW	4	160			11.4		X	X	X					X	X		W	10.9	61.6	4.4	1.3	1.5	10.1	12.0	9.2
IB-2	6,8	T	8	225		4.01	13.9		X	X	X								E	11.0	65.4	4.9	1.4	4.2	7.3	7.4	9.4
IB-3	6,8	T	8	325		5.1	20.8		X	X			X						E	10.7	62.3	4.7	1.3	2.8	9.2	8.2	11.0
Hoot Lake	10	T	16	400					X	X	X		X	X					L	6.4	41.2	2.8	0.6	0.9	11.8	33.0	9.7
IB-10	6,8	C	2	400		0.4	1.1		X	X	X								E	12.7	76.7	5.5	1.6	2.9	5.6	1.4	7.8
IB-1	6,8	SS	3	135		2.1	5.7	VB	X	X	X	X							E	12.2	72.1	5.3	1.4	2.9	9.6	6.0	4.8
IB-6	6,8	SS	5	150		1.9	5.8	TG	X	X	X				X				E	12.6	73.0	5.5	1.3	1.6	7.0	3.6	8.0
IB-7	6,8	SS	5	230		1.9	5.8	TG	X	X	X				X				E	12.1	72.2	5.2	1.6	0.8	7.3	1.6	13.0
IB-11	6,8	SS	2	50		1.3	2.89	TG	X	X	X						X		E	13.3	76.2	5.4	1.5	0.8	9.4	2.1	6.8
IB-12	6,8	SS	3	75		2.1	3.25	TG	X	X	X						X		E	13.3	75.9	5.4	1.4	1.6	8.8	1.6	6.9
IB-13	7,8	SS	4	125		2.1	6.70	TG	X	X	X	X			X				E	12.3	68.3	4.7	1.5	1.2	11.0	3.4	14.5
IB-16	5	SS		150				TG												12.7	67.1	5.3	1.3	2.4	11.9	4.1	7.9
Boiler A	11	SS	7	300				TG	X	X	X	X				X	X		E	11.3	64.8	4.7	1.1	0.8	14.9	11.0	2.7
Fairmont 3	9	SS	4	80				TG	X	X	X					X	X		E	10.9	62.3	4.3	0.5	1.5	9.6	14.2	7.7
Madison 2	9	SS	3	100				TG	X	X	X					X			E	12.0	66.3	4.6	1.3	3.1	7.7	7.4	9.6
St. John 2	9	SS	2	135		2.3	0.49	DG	X	X	X					X	X		E	13.1	72.3	5.2	1.0	0.6	10.5	5.2	5.3
Wilmar 3	9	SS	6	160		3.0		TG	X	X	X	X				X	X	a	W	8.4	49.3	3.3	0.7	1.2	10.9	25.6	9.1
IB-8	6,8	US	7	60		1.9	5.04	SG	X	X	X								E	11.2	67.5	4.5	1.4	0.9	5.7	10.5	9.5
IB-9	6,9	US	7	60		1.9	5.04	SG	X	X	X								E	11.2	67.5	4.5	1.4	0.9	5.7	10.5	9.5
IB-10	6,9	US	1	10				SG	X		X									13.5	77.1	5.6	1.5	1.5	7.8	1.9	4.6
IB-19	6,8	US	1	10				SG	X		X									13.5	77.1	5.6	1.5	1.5	7.8	1.9	4.6
IB-15	7,8	OS		215		4.3	16.3	TG	X	X	X	X								11.9	63.4	4.8	0.9	3.1	9.9	4.2	13.7
Eau Claire	9	OS		60				TG	X	X	X									12.4	65.1	4.6	1.2	2.8	9.1	9.2	8.0
Stout 2	9	OS	45	45				VG	X	X	X					X	X	a	E	12.0	71.4	5.0	1.3	2.8	7.8	4.5	7.3

a - SOx
b - NOx - air register adjustments

VG - vibrating grate
TG - traveling grate
DG - dumping grate
SW - single wall fired
HO - horizontally opposed

T - tangential
C - cyclone
SS - spreader stoker
US - underfed stoker
OS - overfed stoker
W - western coal
E - eastern coal
L - lignite

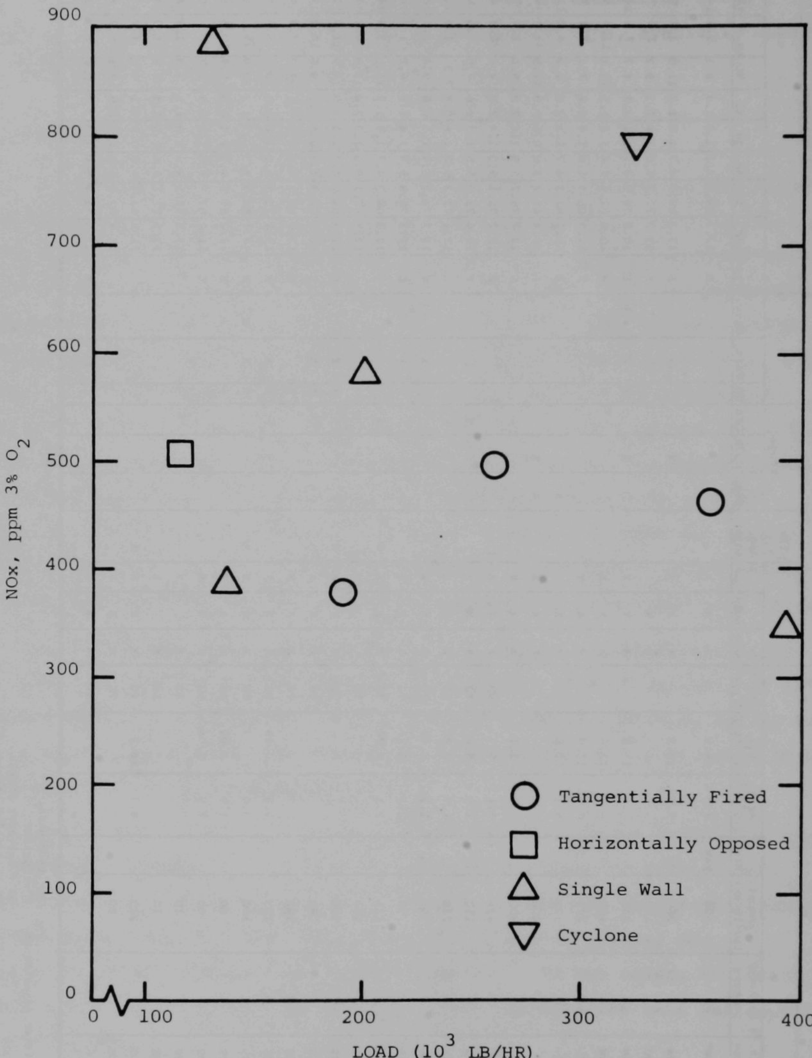


Fig. 3-2. Pulverized-coal-fired industrial-boiler baseline NOx emissions.

The ranges of baseline NOx emission data for coal-fired utility boilers are presented in Fig. 3-3 for comparison purposes. It is apparent that the NOx emission levels for industrial boilers are within the emission range for the low end of the utility boiler capacity range.

Brief reviews of the different types of pulverized coal-fired boilers are given in the following sections. However, the general principles of operation are the same as for utility boilers, and the reader is referred to References 3-12 and 3-13 for a more detailed discussion.

3.3.1 *Cyclone*

The one cyclone industrial boiler baseline test shows a NOx emission of 800 ppm which agrees with the high NOx emission characteristics of utility sized units of this boiler configuration (Fig. 3-3). Baseline data for cyclone utility boilers ranged from 900 to 1500 ppm NO in a prior study, following no apparent relation with boiler capacity (Ref. 3-5). The slightly lower NOx emissions of this industrial cyclone unit may be due to more liberal furnace volumes but also could be just normal unit specific emissions variations. Among coal-fired industrial boilers, the cyclone is recognized as the highest NOx emitter, having an average emission factor of 1.6 lb NOx/MBtu.

Typical cyclone boiler arrangements are shown in Fig. 3-4. The bulk of the combustion air enters tangentially to the cyclone burner at high velocity. The crushed coal is injected at the free end of the cyclone where it undergoes rapid and high intensity combustion. The combustion process is essentially complete before the gases enter the main body of the furnace. The high intensity combustion insures that the ash is heated to a molten state, is thrown outward by centrifugal action, and is allowed to coat the walls of the cyclone. The slag flows down the walls and is tapped off. A secondary purpose of the molten slag covering the walls is that unburnt coal particles are centrifugally thrown out to the walls where final combustion is completed. The molten coating helps to insulate the refractory lined cyclone and promotes the high temperatures required in operation.

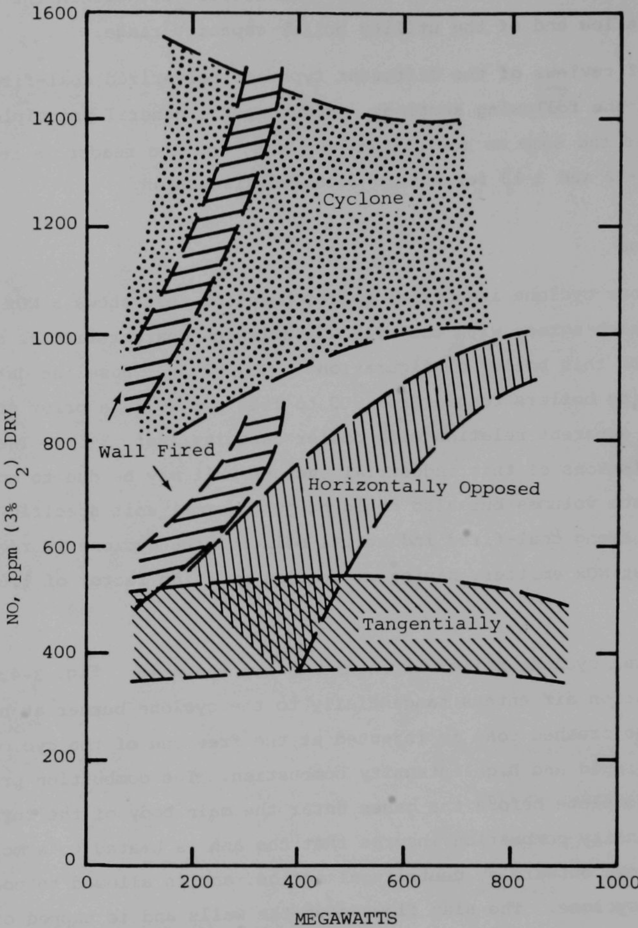


Fig. 3-3. Baseline NO emissions for coal-fired utility boilers (Ref. 3-20).

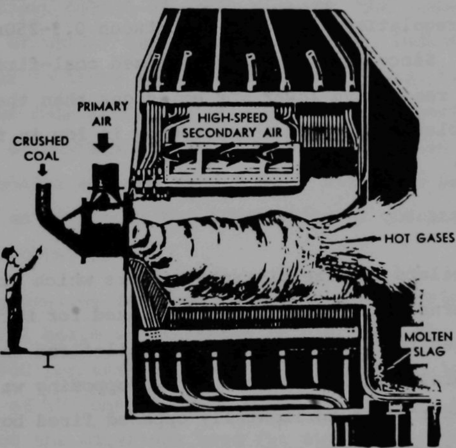


Fig. 3-4. Cyclone furnace (Ref. 3-12).

Some of the advantages of the cyclone boilers are their relatively high efficiencies, low ash loading of the combustion gases, and the ability to burn troublesome high ash/low ash fusion temperature coals. They use crushed, not pulverized coal, thus lowering the energy consumption of fuel preparation. However, this gain is offset by high fan costs for the high pressure air needed to make the cyclone work.

The high intensity combustion process promotes high NOx emissions and this characteristic has greatly reduced the desirability of cyclone furnaces, at least in utility applications where regulations restrict NOx emissions. Currently, the New Source Performance Standards apply to boilers above 250×10^6 Btu/hr which covers the high size range of industrial boilers. Studies considering regulations for boilers between $0.3\text{-}250 \times 10^6$ Btu/hr are underway (Ref. 3-4). Since many of the pulverized coal-fired industrial boilers in this size range have lower NOx emissions than the cyclone units, the choice of the cyclone boiler as a new source is low in the ranking of boiler design types.

3.3.2 Wall-Fired

Wall-fired boilers utilize discrete burners which are arranged on the water walls of the furnace. If one wall is utilized for burner mounting, the furnace is referred to as a face- or single-wall-fired unit. Larger wall-fired units generally employ burners on two opposing walls. This configuration is referred to as a horizontally opposed fired boiler. Horizontally opposed fired units are generally restricted to utility boilers larger than 250 MW (approximately 2,500,000 lb/hr steam flow) due to the cost of construction of the fuel handling system and are generally not found in the industrial boiler population.

Burners for these units are generally arranged in a square or rectangular matrix on the wall. The burners are of a circular design and consist of a coal/primary air nozzle and secondary air register. Each burner is an individual unit, with adjustments or provisions for controlling the amount of air flow and coal/primary air injection to produce a stable flame. Typically, all of the burners are interconnected by a common windbox, which delivers the bulk of the combustion air. However, many new low NOx boiler designs have compartmentalized windboxes that provide air flow control to individual burners.

Due to the basic design of these burners, the number of burners is usually a function of boiler capacity. In general, industrial boilers will have burners similar to those found in utility boilers, but typically fewer in number. From the data presented previously for pulverized coal-fired units, the maximum number of burners was found to be six. While the number of burners used in a boiler may not have a major effect on baseline NOx emission, it will have an effect on the flexibility of operation to implement NOx reduction techniques.

Four tests represent the total baseline NOx emission tests for single wall fired industrial boilers. As shown in Fig. 3-2, the NOx emissions range from 350 to 900 ppm with no apparent relationship to boiler capacity. With the exception of the one NOx data point at 900 ppm, the emissions lie along the low end of the emissions band for single wall fired utility boilers (Fig. 3-3). The high (900 ppm) NOx emission of the one unit may be attributable to wet bottom operation, although this could not be confirmed.

Only one test data point has been obtained on a horizontally opposed boiler in this size range at a base load of 106,000 lb/hr steam. The unit tested was a Riley Turbo fired furnace design, which is a variation of a typical horizontally opposed fired unit. These boilers employ a single row of burners on the opposing walls and the burners are directed in a downward position. While the unit was described as a wet bottomed unit, a type characteristically high in NOx emissions, the NOx emissions from this unit shown in Fig. 3-2 are relatively low (∿500 ppm). Wet bottom utility boilers have exhibited NO emissions between 900 and 1400 ppm at base loads (see Fig. 3-3).

3.3.3 Tangentially Fired

Tangentially fired boilers, manufactured by Combustion Engineering, are often referred to as corner fired units since the coal and air nozzles are aligned vertically along each corner of the furnace as illustrated in Fig. 3-5. Stable burning is achieved by the configuration of the boiler (and burner arrangement) rather than by the individual burner design. At each furnace corner, the column of coal and air nozzles is aligned toward a tangent of a circle about the furnace center. When firing in this manner, one flame will impinge upon the adjacent flame, thus creating a recirculation flow which stabilizes the latter flame. A second effect caused by this firing method is the creation of a large vortex about the center of the furnace. The entire furnace is said to behave as a single burner, therefore exact control over local air/fuel ratios is not necessary. Lean or rich zones will become entrained into the vortex and will be blended for efficient combustion. Resulting flames are large and cooler than the highly turbulent combustion conditions characteristic of wall fired units.

These differences in combustion intensity have contributed to characteristically low NOx emissions from these units. This is especially true of utility sized boilers as illustrated in Fig. 3-3. For these units, baseline NOx emissions range from 350 to 550 ppm with little effect of boiler capacity on emission levels. The limited data on tangentially fired industrial sized units are within this range. An examination of Fig. 3-2 suggests, however, that the tangentials are not the lowest NOx emitters but rather have emission levels comparable to wall fired units in the same industrial boiler capacity range.

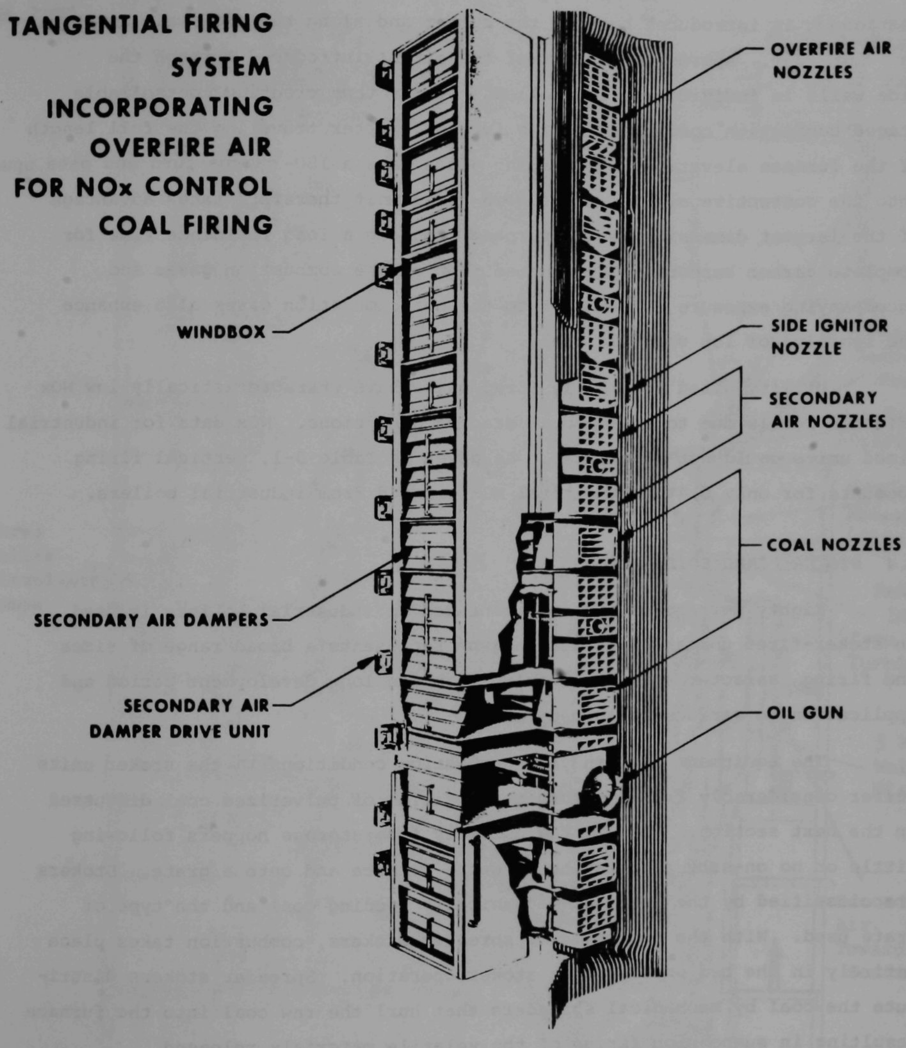


Fig. 3-5. Typical windbox of tangential firing system.

3.3.4 Vertically Fired

In a vertically or down-fired unit, the pulverized coal is injected from the roof location rather than from the side walls or the corners. Combustion air is introduced both at the burner and along the side wall as shown in Fig. 3-6. Approximately 85% of the air is introduced through the side walls in individually controlled sections thus creating controllable staged combustion conditions in the furnace. After traveling the full length of the furnace elevation, the burning gases make a 180-degree turn and pass upward into the convective section. The down-fired unit therefore takes advantage of the largest dimension in the furnace creating a long residence time for complete carbon burnout. The reverse flow of the combustion gases and accompanying exposure of raw coal to the hot combustion gases also enhance the ignition of low volatile coals.

Utility sized vertically fired units have characteristically low NOx emission levels due to the natural staging conditions. NOx data for industrial sized units could not be located. As given in Table 3-1, vertical firing accounts for only 0.4% of the total NOx emitted from industrial boilers.

3.4 STOKER-FIRED BOILERS

Eighty percent of the coal consumed in industrial boilers is used in stoker-fired units. This design type represents a broad range of sizes and firing characteristics reflecting both its long development period and application to various coal conditions.

The equipment used and the combustion conditions in the stoker units differ considerably from the suspension firing of pulverized coal discussed in the next section. Coal is fed directly from storage hoppers following little or no on-site preparation into the furnace and onto a grate. Stokers are classified by the means of mechanically feeding coal and the type of grate used. With the exception of spreader stokers, combustion takes place entirely in the bed under proper stoker operation. Spreader stokers distribute the coal by mechanical spreaders that hurl the raw coal into the furnace resulting in suspension firing of the volatile materials released.

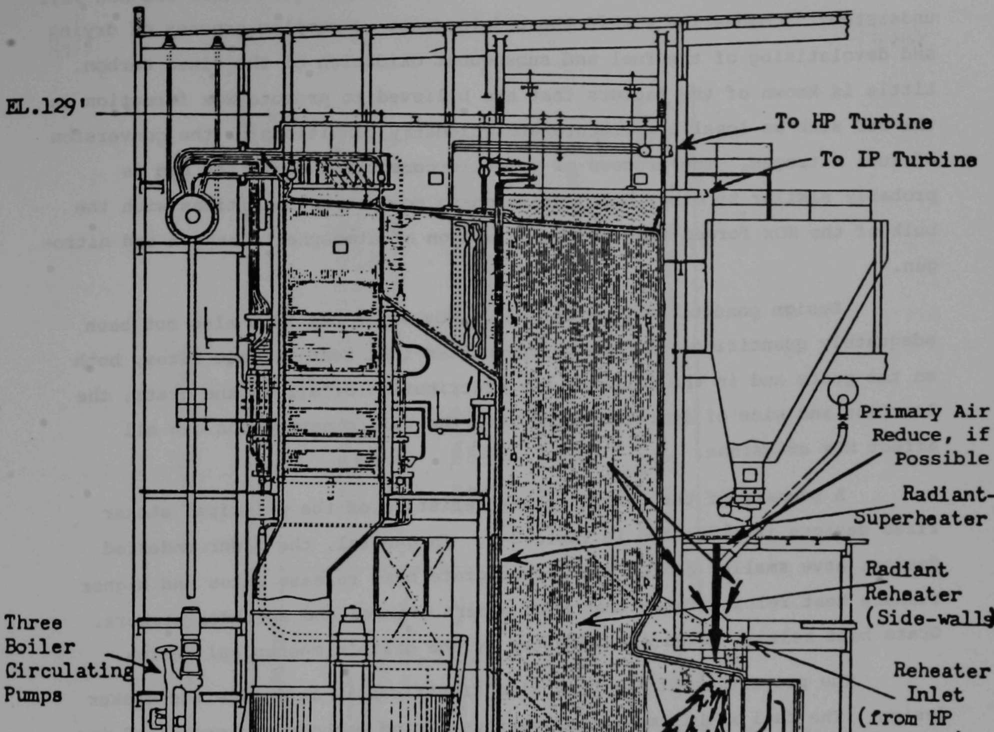


Fig. 3-6. Vertically fired boiler showing the open-furnace configuration.

The mechanisms of formation of NOx in stoker-fired units are not well understood. Combustion within the bed involves a complex process of drying and devolatizing of the fuel and subsequent oxidation of the fixed carbon. Little is known of the factors that are believed to promote NOx formation in the bed such as local temperature/stoichiometry conditions or the conversion of fuel nitrogen. The process of volatile combustion above the bed is probably similar to other homogeneous phase combustion conditions with the bulk of the NOx formed from thermal fixation of atmospheric oxygen and nitrogen.

Design conditions that influence NOx emissions have also not been adequately quantified. It can be speculated that heat release rates, both on the grate and in the furnace; the distribution of air on the grate; the location and size of ignition arches, and the wall construction can all affect NOx emissions.

A summary of the general characteristics of the principal stoker fired designs is presented in Table 3-5. In general, the older underfed designs have smaller grates with lower grate heat release rates and higher furnace heat release rates than more modern overfed and spreader stokers. Grate heat release rates are affected by the grate's mechanical design.

The properties of the coal also significantly influence the stoker design. The fuel requirements for various firing methods are presented in Table 3-6. The important parameters include size, ash content and fusion temperature. Coal size is important in maintaining proper bed conditions. Fine material will sift through the grate or be entrained by the combustion air. Too large material will be removed from the grate prior to complete combustion. Important qualitative measures of the coal include "slacking" or the tendency of the coal to break up during shipment and the coal's "friability" or tendency to break into fines on heating. The ash content will determine both the insulating property of the ash on the bed and the tendency to form "clinkers."

The following sections will discuss in detail the characteristics of the various stoker types considered in this study. Included are the baseline NOx emission data available for each unit type.

Table 3-5. Coal Firing Methods for Industrial Boilers[a]

Firing Method	Grate Area Size Range, m^2 (ft^2)	Grate, MJ/m^2 ($Btu/hr/ft^2$)	Furnace Construction	Max. Furnace Heat Release MJ/m^3 (Btu/ft^3)	Boiler Capacity Range, Mg/hr (lb/hr)	Load Response
1. Underfed Stoker						
Single Retort						
Stationary Grate	0.9-4.5 (10-48)	2839 (250,000)	Refractory	1676 (45,000)	4.4-22 (2,000-10,000)	Poor
Reciprocating Grate	1.4-4.6 (15-50)	3975 (350,000)	Refractory	1676 (45,000)	4.4-33 (2,000-15,000)	
Reciprocating Grate	3.3-11.6 (36-125)	4826 (425,000)	Water Cooled	2235 (60,000)	22-99 (10,000-45,000)	
Multiple Retort	3.3-47 (35-500)	6814 (600,000)	Partial to Full W.C.	1304 (35,000)	44-662 (20,000-300,000)	
2. Overfed Stoker						
Chain Grate	4.6-65 (50-700)	5678 (500,000)	Partial to Full W.C.	1118 (30,000)	55-551 (25,000-250,000)	Fair
Traveling Grate	4.6-65 (50-700)	5678 (500,000)	Partial to Full W.C.	1118 (30,000)	55-551 (25,000-250,000)	
Vibrating Grate	1.4-23 (15-250)	4543 (400,000)	Partial to Full W.C.	1118 (30,000)	13-221 (6,000-100,000)	
3. Spreader Stoker						
Stationary Grate	2.6-8.4 (28-90)	5110 (450,000)	Refr to Partial W.C.	1118 (30,000)	11-88 (5,000-40,000)	Good
Dumping Grate	2.6-15.8 (28-170)	5110 (450,000)	Refr to Partial W.C.	1118 (30,000)	11-165 (5,000-75,000)	
Traveling Grate	9.3-44.6 (100-480)	8517 (750,000)	Partial to Full W.C.	1118 (30,000)	165-771 (75,000-350,000)	
Vibrating Grate	4.6-13.9 (50-150)	6814 (600,000)	Partial to Full W.C.	1118 (30,000)	11-165 (5,000-75,000)	
Oscillating Grate	27.9 (300)	6814 (600,000)			331 (150,000)	
4. Pulverized Coal	---	---	Water Cooled	N/A	77 (35,000) up	Excellent
5. Cyclone Furnace	---	---	Water Cooled	N/A	187 (85,000) up	

[a]Reference 3-9.

Table 3-6. Fuel Requirements for Various Firing Methods[a]

	Firing Type	Coal Type[(g)]	Sizing	Ash, %	AST °K (°F)
Underfed	Single Retort	Coking and caking Free burning	2.54 to 3.81 cm (1" to 1-1/2") nut and slack [<50% through 6.4 cm (1/4") screen]	<10%	1589(2400) [(a)]
Underfed	Multiple Retort	Free burning coal Tends to drift[(b,f)]	5.08 cm (2") nut and slack [<50% through 6.4 cm (1/4") screen]	<10%	1589 (2400)
Overfed	Chain Grate	All except caking bituminous[(f)]	2.54 cm (1") nut and slack	<6% on dry basis	1422 (2100)[(c)]
Overfed	Traveling Grate	All except caking bituminous[(f)]	2.54 cm (1") nut and slack - will handle fine coal	<6% on dry basis	1422 (2100)[(c)]
Overfed	Vibrating Grate	All types[(f)]	2.54 cm (1") nut and slack - less fines preferred	<6% on dry basis	(<1422)(<2100)
Spreader Stokers	Stationary Grate	All types	1.91 cm(3/4") nut and slack	---	---
Spreader Stokers	Dumping Grate	All types	1.91 cm(3/4") nut and slack	---	---
Spreader Stokers	Traveling Grate	All types	1.91 cm(3/4") nut and slack	---	---
Spreader Stokers	Vibrating Grate	All types	1.91 cm(3/4") nut and slack - less fines preferred	---	---

Notes

(a) Reduced burning rate for lower ash softening temperatures.

(b) Reduce fuel rate 12% with free burning coal in open furnace. Long rear arch improves combustion in free burning coal.

(c) Lower fusion temperature ash can be accommodated at lower burning rates.

(d) Preheated air temp. up to 450°K(350°F) can generally be used with stoker firing without excessive maintenance.

(e) Preheated air temp. for pulverized coal drying ranges from 450°K (350°F) to 672°K (750°F) depending on moisture

(f) Fuel to be delivered across the width of the stoker hopper without size segregation.

(g) Excluding anthracite.

[a]Reference 3-9.

3.4.1 *Underfed Stokers*

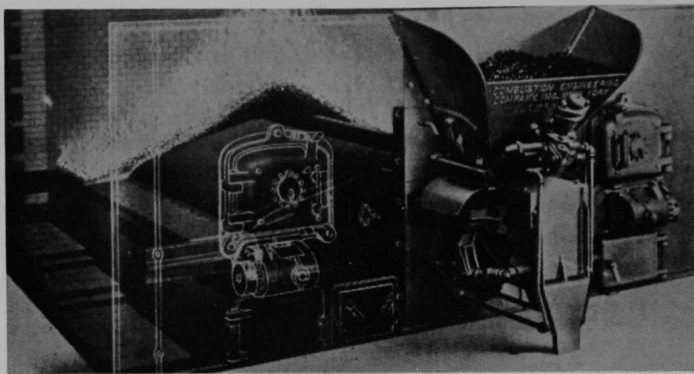
3.4.1.1 *Single Retort Stokers*

Single retort underfed stokers, illustrated in Fig. 3-7, are the earliest type of underfed stokers. These stokers operate by feeding coal to the lower portion (retort) of the fuel bed either in small increments by a power driven ram or continuously by a screw conveyor. Moisture and volatile matter are driven off in the lower part of the fuel bed. The combustible gas emitted by the lower fuel bed is burned with combustion air above the fuel bed. Coked coal is forced upward through the retort and spreads over the side grates where combustion is completed. Dead plates at the stoker slides are provided for collecting ash and refuse.

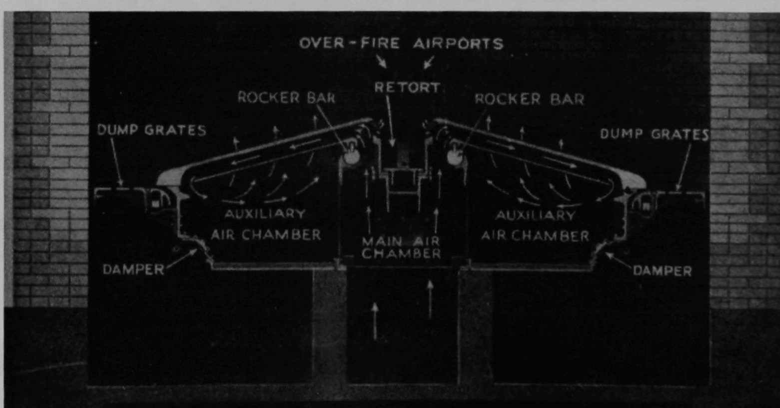
While the earliest patents date from 1838, intensive development of this stoker occurred between 1889 and 1906. Important improvements were reciprocating retort bottom with auxiliary feed rams to distribute the coal from front to rear; moving grate bars to break up coke formations and distribute coal laterally across the grate; hollow, air-cooled grate bars; and side dumping grates for discharging ash. These features are incorporated into the majority of single retort underfed stokers in service or on the market today.

A number of distinctive designs are manufactured ranging from 10 to 125 sq ft of grate area (Ref. 3-13). These stokers are generally considered applicable up to 35,000 lb/hr steam.

Fuels ranging from lignite to anthracite are successfully burned; however, single-retort underfed stokers are principally used for burning eastern coking bituminous coals and those midwestern free-burning coals with sufficiently high ash softening temperatures (>2400 °F) to avoid clinkering in the relatively thick fuel beds. Most fuel should be 3/4 inches in size, with maximum size 1-1/2 inch, and not more than 50 percent to pass through a 5/16" round sieve (Ref. 3-12). Easily friable coals can be used with larger lump size because of the degradation occurring in transit and handling.



View with part of the front and fuel bed in phantom to show interior and fire on rear part of grate



Cross-section showing air distribution system

Fig. 3-7. Single retort stoker.

Single retort underfed stokers do not require ignition or combustion arches to provide for sufficient mixing and burning of the combustible gases. Combustion rates, in terms of Btu per hr-square foot of grate area range from 300,000 for the smaller stokers with refractory furnaces up to 425,000 for the larger stokers in water cooled furnaces (Ref. 3-9). As given in Table 3-5, these greater heat release rates are relatively low compared to other stoker designs. Since NOx emissions are believed to be a function of this grate heat release rate, this unit type would be expected to have low NOx emission levels. Heat liberation rates up to 45,000 Btu per cubic foot of furnace volume are acceptable for refractory furnaces and up to 60,000 Btu per cubic foot with water cooled furnaces.

3.4.1.2 Multiple Retort Stokers

Multiple retort stokers were developed shortly after 1900 to fill a need for larger stokers and to meet the growing steam demand. This type, illustrated in Fig. 3-8, consists of a series of inclined retorts with tuyeres between for air admission. Each retort is equipped with a primary ram which feeds coal at the head of the retort. Secondary pushers slowly move the coal to the rear and complete combustion before the refuse reaches the discharge section which can be one of three types: Clinker-grinder, continuous-discharge, or dump-grate.

The multiple retort underfed stoker works best on crushed coal with a top size of 2", with not more than 50% able to pass through a 1/4" round hole screen; a volatile content between 20% and 30%; ash content of 6% to 8%, and an ash softening temperature above 2400 °F. The ash should not contain more than 15% Fe_2O_3 (Ref. 3-13).

Air blockage will inhibit complete oxidation of carbon monoxide to carbon dioxide and hydrocarbons to oxidized hydrocarbons resulting in lower heat rates and a loss in boiler efficiency.

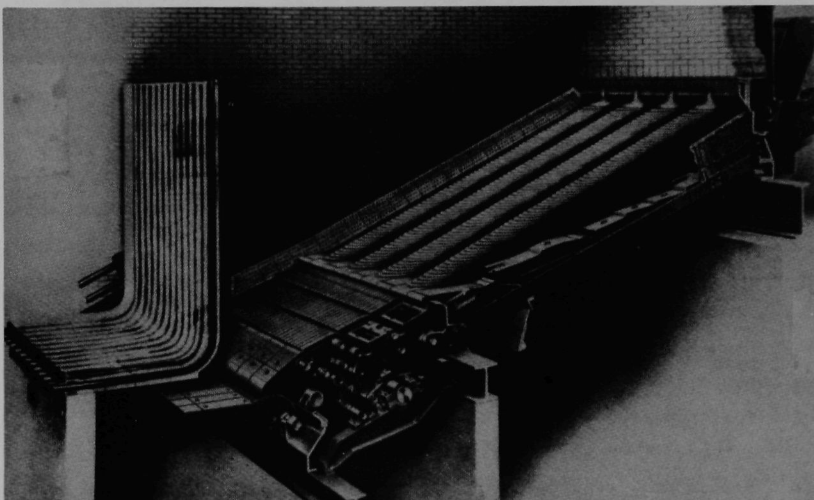


Fig. 3-8. Multiple-retort stoker showing details of components (Ref. 3-12).

Multiple retort underfed stokers may employ rear arches to improve ignition. Arches are especially important for nonagglomerating coals which do not form coke in the furnace. Heat liberation rates are limited to approximately 35,000 Btu per cubic foot. Load capacities vary up to 500,000 lb/hr steam utilizing rear wall and side wall water cooling (Ref. 3-14).

The baseline NOx emissions for the underfed stoker group are presented in Fig. 3-9. Only four tests have been performed on these boilers, despite their relatively large proportion in the industrial boiler class. However, most units in the field are other designs and no new underfed units are being sold. These tests indicate low NOx emissions for underfed stokers, ranging between 250 and 350 ppm. Each pair of boilers tested consisted of similar units at the same location. The base load for the two small boilers was not exactly known, but was assumed to be about 8,000 lb/hr steam. This is the extreme low end of the industrial boiler category. The base load for the other two boilers was also on the low side, 47,500 lb/hr steam.

3.4.2 Overfed Stokers

Chain or traveling grate stokers illustrated in Fig. 3-10, can be described as assemblies of moving belts transporting coal from the coal hopper to the furnace exit. As the coal enters the furnace, radiant heat from the furnace walls heats the coal and ignites it. The coal bed thickness decreases as the belts traverse the furnace length. Ash and residue are deposited by the grate in an ashpit at the furnace rear.

The grate surface of a chain grate stoker consists of a series of cast-iron or steel links connected by bars to form an endless chain. In the traveling grate or bar-and-key design, a series of cast-iron sections or keys are mounted on carrier bars which are fastened to two or more drive chains to form an endless conveyor. The links of the chain grate stoker are assembled so that a scissoring action occurs when the chain goes over the end drums. This action tends to break loose any ash or clinker adhering to the grate surface or plugging the air spaces between links. There is no such relative motion between adjacent keys on the traveling grate design, hence badly clinkering coals are not well suited. Chain grate stokers are very effective for minimizing clinker and ash deposits between links.

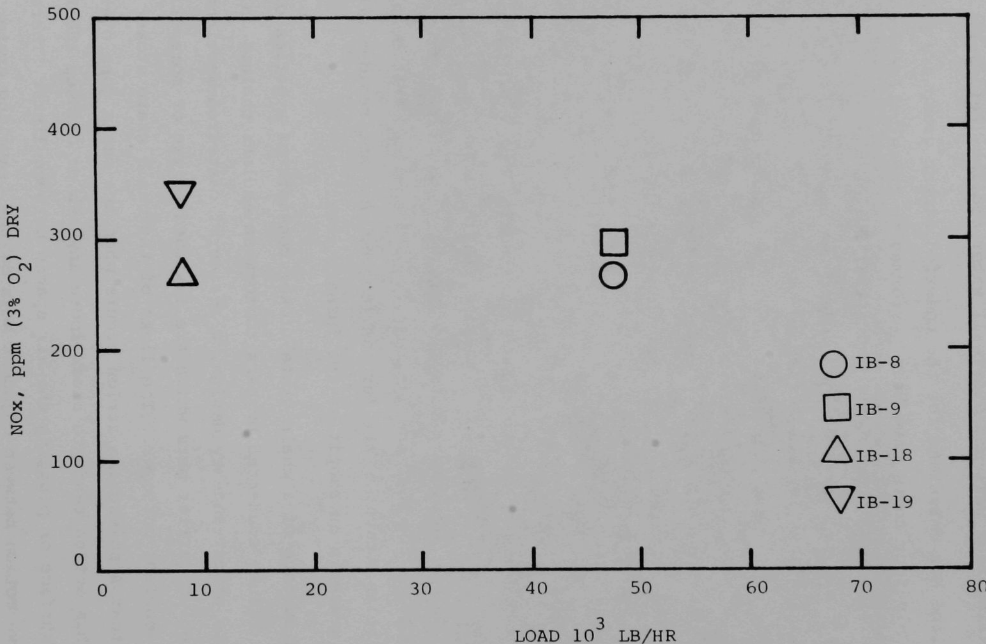


Fig. 3-9. Industrial-sized underfed-stoker baseline NOx-emission levels.

Natural draft chain-grate stokers were developed in the latter half of the 19th Century and offered commercially in 1896. Traveling grate stokers were introduced commercially in 1893. Natural draft stokers have a free air space through the grate of 18% to 22% and operate with a draft loss through the fuel bed of one-tenth to five-tenths of an inch of water (Ref. 3-12). A coarse coal with few fines is preferred.

Forced draft stokers, introduced in the 1920's to meet the demand for higher capacity and better performance, have generally made the natural draft design obsolete. Forced draft stokers have a free air space through the grate of 6% to 10% and consequently can burn finer coal. Normally, draft loss through the fuel bed is one to two inches water gage. These stokers are suitable for boiler sizes from 25,000 to 250,000 lb/hr steam (Ref. 3-12).

A great deal of experimentation has been done on furnace design to provide satisfactory ignition and eliminate stratification resulting in unburned gases or carbon carry-over. Initially front, rear, or combinations of front and rear arches were relied on to promote ignition and mixing. More recently, high-velocity air jets have replaced front arches to provide turbulence for completing combustion of distilled volatile matter (see Fig. 3-10). Long rear arches are still considered effective in promoting burnout and transporting incandescent particles to the front of the stoker.

Several coal types can be burned in chain grate or traveling grate stokers. The notable exception is highly coking bituminous coal which inhibits air passage through the fuel bed. The result is excessive carbon carryover in the ashpit.

Maximum continuous burning rates for bituminous coals range from 425,000 to 500,000 Btu per square foot per hour (Ref. 3-12). The lower burning rate applies to high moisture (>20%), high ash (>20%) coals. Low ash coals (less than 8%, dry basis) will not protect the grates from overheating and are considered unsuitable for chain grate or traveling grate stokers.

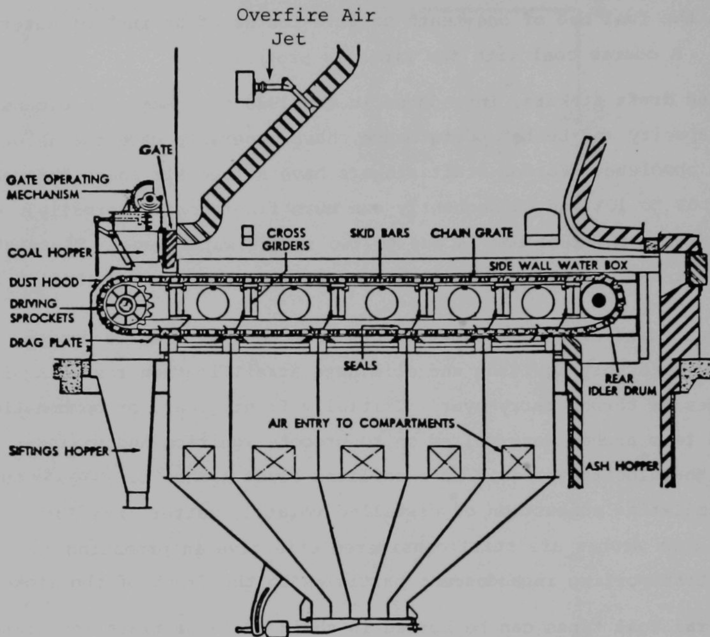


Fig. 3-10. Chain or traveling grate stoker (Ref. 3-12).

Vibrating grate stokers are a more recent development in which coal from the hopper is fed onto an inclined grate and moved over the grate by intermittent vibrations as illustrated in Fig. 3-11. The grate surface is mounted on a grid of water tubes tied into the boiler circulation and the entire grate structure is supported by flexing plates which allow the grate to be vibrated as a unit. These units are available up to a boiler capacity of 100,000 lb/hr and can be operated up to 400,000 Btu per square foot of grate surface per hour. The heat-liberation rate is usually limited to 30,000 Btu per cubic foot of furnace volume per hour. Overfire air jets are used to provide turbulence for complete combustion of the volatile matter. The vibrating-grate stoker will operate successfully with caking coals but an excessive amount of fines will create problems with fine coal or ash sifting through the grate.

The absence of a revolving grate allows the air flow through the bottom of the grate to be partitioned and individually controlled. In the one vibrating grate overfed stoker represented in this study, the grate air was split into five sections, each extending normal to coal flow. Each of the sections was equipped with a damper control allowing very good air flow control along the coal combustion path. These adjustments allow fine tuning of the air flow and the flexibility for proper combustion of coals with different burning characteristics. In addition, overfire air nozzles were installed for volatile burnout.

Fig. 3-12 presents the baseline NOx data for overfed stokers available in the literature. It can be seen that, for these tests, the baseline NOx emissions are low. The three baseline tests all fall between 150 and 250 ppm NOx which are of the same order as the underfed stokers tested. For these three tests, there appears to be no correlation between NOx emissions and boiler size; however, this is a very limited sampling.

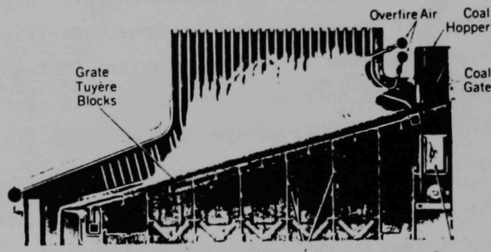


Fig. 3-11. Water-cooled vibrating-grate stoker (Ref. 3-14).

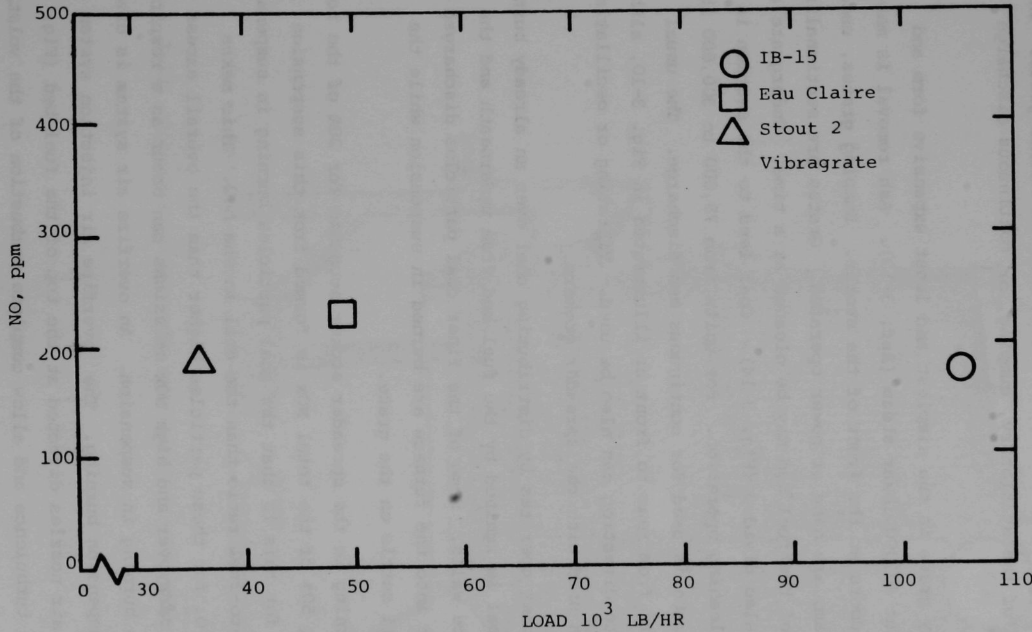


Fig. 3-12. Baseline NO emissions for overfed stokers at various operating loads and normal excess O_2 .

3.4.3 Spreader Stokers

The modern spreader stoker, illustrated in Fig. 3-13, consists of one or more feeder units mounted on the boiler front, each comprising a coal hopper, a feeder that regulates the flow of coal, and a distributor rotor that throws the coal into the furnace and distributes it on the grate. The stoker grates may be of the stationary, dumping, or continuous discharge type.

The stationary grate is the simplest and least expensive form and is suitable up to about 40,000 lb/hr steam (Ref. 3-13). Ash removal is manual through grate level doors at the front of the stoker. Dumping grates, used up to 75,000 lb/hr steam, are hand or power operated. Grates are sectionalized so that one portion of the fuel bed may be cleaned at a time. Undergrate air plenum chambers are also divided (Fig. 3-14). Coal feed to the section is stopped during the cleaning operation. For units from 75,000 to 300,000 lb/hr steam, a traveling grate is used for continuous ash discharge. The usual direction of travel is from rear to front as illustrated in Fig. 3-10, although travel in the opposite direction can also be used. Vibrating or oscillating grates have also been used with the spreader stokers.

A spreader stoker operates by distributing coal over an already burning fuel bed. The coal is ignited by the fuel bed from underneath and the radiation from furnace walls. Some of the finer coal particles discharged by the distributor rotor into the furnace are burned in suspension while the coarser particles will settle on the grate.

Suspension burning in the spreader stoker accounts for 20% of the total coal burned; however, 50% of the total NOx is formed from this suspension burning. The reason for this is that the coal particles burning in suspension burn at a higher air-to-fuel ratio than the coal in the bed. This makes the effective excess O_2 for these particles higher than the overall excess O_2 of the furnace. Carbon carryover and high NOx emissions can occur as a result of partial coal particle burning in suspension. An overfire air system is essential in successful suspension burning. The overfire air injection system consists of banks of air nozzles directed at the top of the fuel bed (Fig. 3-15). These nozzles promote turbulence and allow complete combustion of the volatiles and fine suspended coal particles.

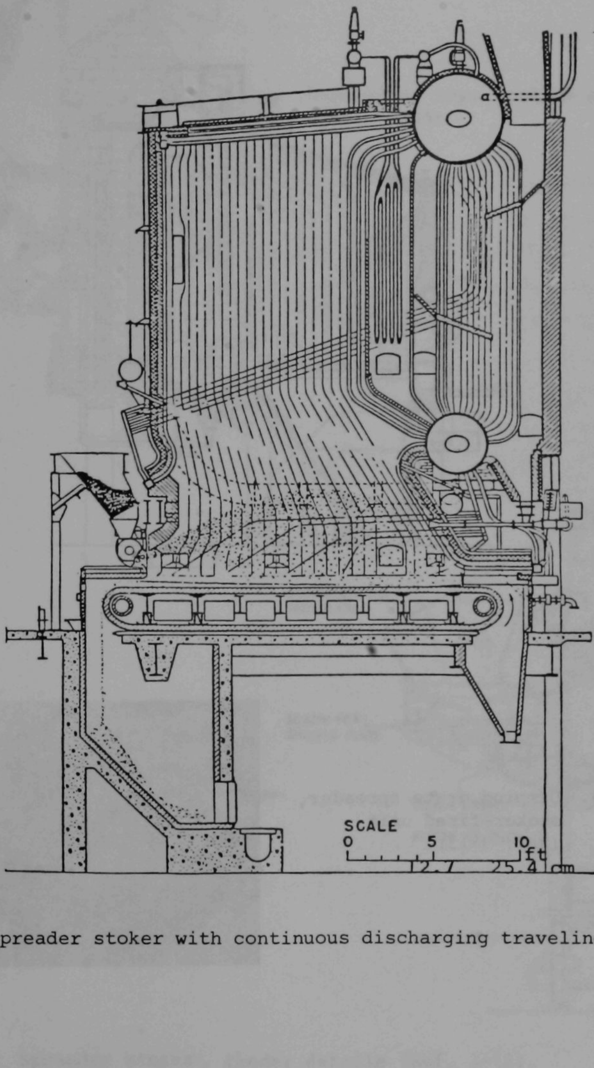


Fig. 3-13. Spreader stoker with continuous discharging traveling grate.

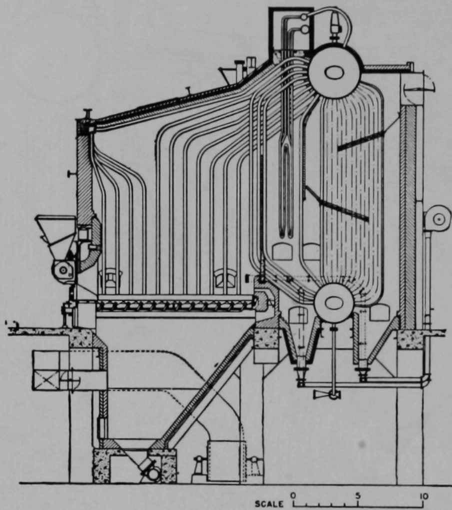
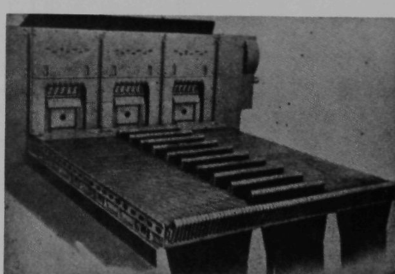
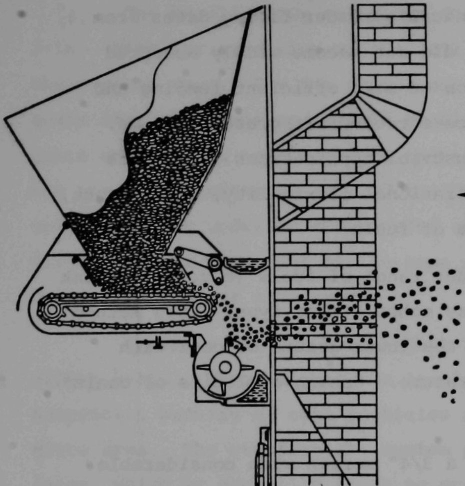
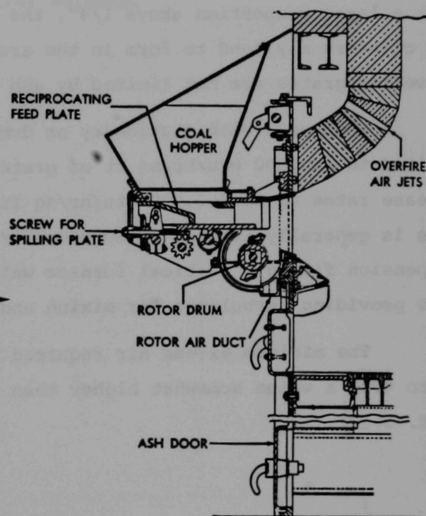


Fig. 3- 14. Dumping grate spreader, stoker-fired unit (Ref. 3-13).





Continuous type feed to spreader stoker stoker rotor



Reciprocating type feed to spreader stoker rotor. Note overfire air jets for breaking up stratified gases.

Fig. 3-15. Spreader stoker, feeder details (Ref. 3-12).

As with other stoker types, mechanical spreader firing dates from the 1800's. However, the spreader stoker did not become widely accepted until the 1930's following the introduction of more efficient feeding and distribution mechanisms and high-resistance forced-draft grate surfaces. The spreader stoker now ranks high in industrial applications due to its relatively high combustion efficiency, operational flexibility, maintenance, capacity, and ability to burn a wide range of fuels.

The spreader stoker can burn a wider range of fuels (e.g., high rank Eastern bituminous, lignite, etc.) than any other stoker type. This method of firing was developed primarily to burn the lower grades of coal with high ash content and low ash fusion temperature. Caking qualities of coals have little effect on performance.

The fuel should be sized to pass a 3/4" screen with considerable range in particle size to produce a uniform fuel bed. If the particles are all of one size, much of the fuel will fall on one portion of the grate. Larger lumps tend to increase ashpit losses. When the coal is too coarse with a large proportion above 1/4", the fuel bed may not burn down evenly and clinkers may tend to form in the areas containing the larger sizes. Traveling grates are not limited by ash content.

When used with stationary or dumping grates, heat release rates are limited to 450,000 Btu/hr/sq ft of grate. With traveling chain grates, heat release rates up to 900,000 Btu/hr/sq ft are possible. The furnace heat release rate is generally limited to 30,000 Btu/cu ft because of the greater amount of suspension firing. Vertical furnace walls are preferred with overfire air jets providing turbulence for mixing and combustible burnout.

The minimum excess air required for spreader stokers is approximately 25 to 40%, a value somewhat higher than that used for chain grate stokers (Ref. 3-12).

The baseline NOx emissions for spreader stokers are shown in Fig. 3-16. With the exception of two, all of the boilers are of the traveling or chain grate type. The two cases, one a dumping grate and the other a vibrating grate stoker, appear to exhibit baseline NOx emissions similar to the traveling grate units. The emissions for these spreader stokers range from 300 to 600 ppm. NOx emissions are 200 to 300 ppm higher for the spreader stoker units than for underfed and overfed units. These baseline NOx emissions are slightly lower than, but of the same order as, wall fired pulverized coal boilers of similar size range.

Spreader stokers have higher NOx emissions than underfed and overfed stoker units. These higher NOx levels can be associated with the partial suspension burning of coal particles and higher heat release rates per grate area. The overfire air system promotes burnout by increased turbulence, which is generally known to promote NO formation in all types of flames. The increase in heat release rates has also been correlated with increased NO formation due to higher gas temperatures and the types of flames required to complete combustion in smaller volumes.

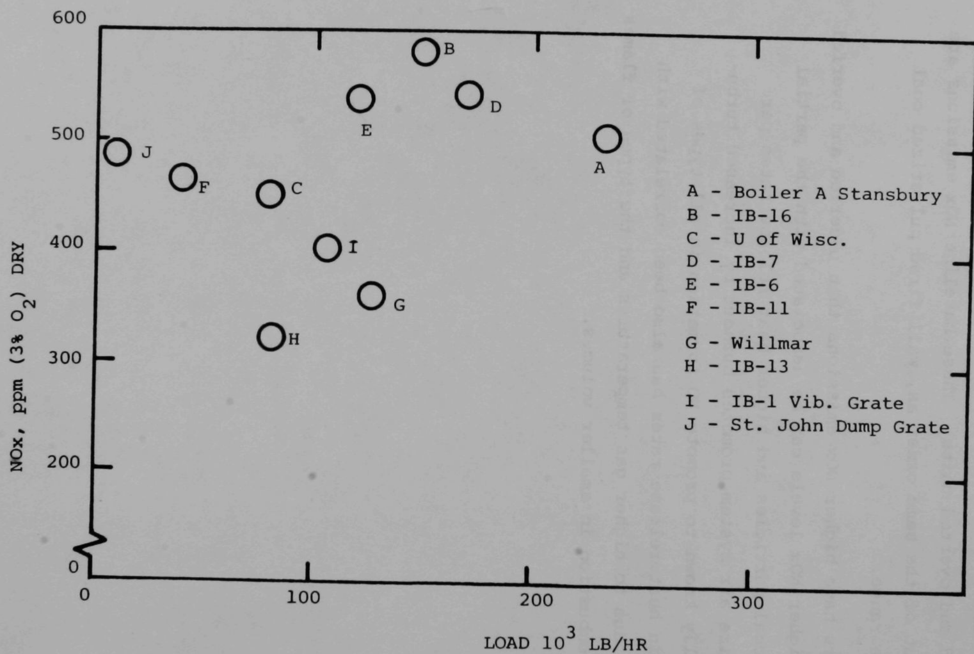


Fig. 3-16. Baseline NO emissions for spreader stokers at various operating loads and normal excess O_2.

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4 COMBUSTION MODIFICATIONS TO REDUCE NOx EMISSIONS

Combustion modifications can be effectively used to control NOx emissions from utility sized boilers of any fuel type -- gas, oil or coal -- in order to comply with federal and regional NOx regulations. These modifications have also been effective in reducing emissions to meet the NSPS (New Source Performance Standard) for new boilers. These techniques include low excess air operation, staged combustion and flue gas recirculation. Flue gas recirculation has been found to have limited effectiveness in reducing NOx in coal-fired utility boilers (Ref. 4-1). This conclusion also applies to industrial coal-fired boilers and thus flue gas recirculation will not be discussed in this report. The other combustion modification methods are reviewed briefly below and their effect on NOx emissions for specific boiler types in Section 4.2.

Low excess air (LEA) involves operation of the boiler with a reduced amount of combustion air. Reducing the excess air levels results in a decrease in the availability of oxygen to form NOx through both thermal fixation of atmospheric oxygen and nitrogen and conversion of fuel nitrogen. The extent to which this technique can be applied is limited by the amount of air required to complete combustion within the furnace with a safety margin for various fluctuations in boiler operation (fuel flow, distribution, steam demand, variability of controls, etc.). The limitations of LEA operation are incomplete carbon burnout in ash, CO emission, smoke formation, and clinkers on the grate, as well as increased corrosion or slagging if improperly implemented.

Staged combustion is a means of delaying combustion as the result of decreased oxygen availability in the early part of the flame followed by addition of the balance of the air and burnout downstream after significant heat removal has taken place. Staged combustion can be implemented in three ways: (1) biasing of coal and/or air mixtures between burners in an array, (2) burners-out-of-service (BOOS), and (3) the use of overfire air ports. The limitations to the use of staged combustion are similar to those encountered in LEA firing. (For the reader not intimately familiar with these three staged combustion techniques, a discussion of their principles of operation and respective features is included in the next few pages.)

All three forms of staged combustion attempt to reduce the oxygen availability in the active flame regions (where NOx can be formed) while providing sufficient air further downstream to complete fuel burnout. The second stage air brings the overall level of O_2 to near normal levels and provides for complete burnout of CO and carbon. The major difference between staged combustion and LEA is that with staged combustion, the primary zone (active first stage combustion region) local O_2 level can be reduced below that attainable with LEA alone. In fact, with staged combustion, it is desirable to achieve fuel-rich conditions in the primary zone. With the further reduction of the O_2 levels, in conjunction with staged firing, the potential for additional NOx reductions exists. (This process bears some similarity to the stratified charge principle of combustion in IC engines.) Using LEA requires careful evaluation of the impacts of secondary pollutants as well as potential operational problems.

Bias firing is the least effective method of staging the combustion process in the furnace. Biasing is accomplished by either reducing the fuel distribution to the upper levels of burners or increasing the air distribution to these same burners. In either case, the net result is to decrease the O_2 concentration at the lower elevation of burners while increasing the O_2 at the top with the overall O_2 level remaining relatively unchanged from baseline.

Burners-out-of-service (BOOS) is a more advanced form of biased firing where the fuel flow is terminated to a select number of burners while the air registers are left open. The fuel flow from the BOOS is diverted to other in-service burners causing them to operate fuel-rich. "Normal" applications may leave all of the active burners operating at a uniform air register while the out-of-service burner air registers sometimes are adjusted to alter the amount of staging. Obviously, the fuel flow through the in-service burners must increase or a reduction in boiler capacity will occur. BOOS is one of the most effective staged combustion techniques in that it allows sufficient segregation of fuel-rich and air-rich combustion zones to minimize NOx yet still permits eventual mixing and carbon burnout without smoke or soot formation.

Overfire air (OFA) is another method of staging with more physical separation between the fuel-rich burner zone and the point of second stage air addition. Rather than alter the fuel and air flows at the burners, a set of overfire air ports is installed above the burner region. In a manner similar to BOOS, these ports are used to inject combustion air to permit complete combustion. For effective overfire air operation, these ports require a separate air flow control and careful design to obtain optimum results. In some units, the air is simply diverted from the combustion air windbox providing poor air penetration and mixing with a loss in operating excess air level or increased smoking tendencies. If properly implemented, overfire air ports offer advantages over BOOS including no reduction in boiler capacity due to coal feed limitations, and better design of air flows (for optimum CO burnout with minimum backflow into the active combustion zone.) While OFA ports are easily added in a new boiler design, retrofit applications become more costly and more difficult to construct because of boiler and windbox modifications plus occasional space limitation problems.

As mentioned previously, these staged combustion techniques have been developed and are currently implemented in utility boilers. All coal-fired utility boilers greater than 1,000,000 lb/hr steam are pulverized coal-fired. As such, the nomenclature of the various methods of staged combustion has been adapted from these pulverized coal units. While these techniques are readily applicable to pulverized coal-fired industrial sized units, in certain cases they are not appropriate for stoker-fired units. For example, there is no comparable technique for BOOS operation.

Confusion can arise from the similar names given to an overfire air port on a pulverized coal-fired boiler and the overfire air nozzles on a stoker unit. The overfire air nozzles in a stoker are standard equipment and necessary in the operation of a stoker unit. These nozzles are placed about 1-1/2 to 2 feet above the fuel bed on both the front and back walls of the boiler. No more than 15% of the air is admitted through these nozzles. The objective of these overfire air nozzles is to increase turbulence to promote the mixing of devolatilized fuel with the air and aid CO burnout.

On the other hand, overfire air ports for NOx control typically admit up to 25% of the total air and are situated several feet above the burner level. However, stoker-fired tests have been run to evaluate the influence of air flows to undergrate and overfire air nozzles. These cases have been identified as a stoker air adjustment or biasing of air flows -- not an OFA staged combustion technique. A method of injecting combustion air through unused gas or oil burners located in a side wall or rear wall of the boiler has also been attempted in stokers. In this case, it is equivalent to the installation of OFA ports in a PC boiler and is identified as an OFA test. However, it should be realized that the use of auxiliary gas/oil burners to inject the secondary combustion air may be far from optimum in terms of an NOx control technique. It is apparent that a need exists to study the influence of overfire air port position, air flow, penetration, and turbulence on coal-fired industrial boiler NOx reduction.

No tests have been conducted using overfire air ports to achieve a staged combustion condition for a coal-fired industrial boiler. This method has been shown to be effective in coal-fired utility boilers (Ref. 4-1). The potential advantages of OFA ports over biased or BOOS operation are (1) no direct losses in boiler capacity occur and (2) better control of the staging process can be achieved. The installation of ports allows air injection at points further downstream of the burners while under BOOS operation, the injection point is solely dependent upon burner spacing and firing rates. Increased first stage residence times at reduced stoichiometries proportional to the distance between the burners and the staged air injection point have been shown to be effective in reducing NO emission (Ref. 4-2).

In the following sections, each boiler type will be taken in turn and the available data on LEA and the forms of staged combustion evaluated. Due to limited data for the types of staged combustion in stokers, all stokers will be discussed as a single group. NOx reductions will be expressed both in terms of corrected emission levels (as a volumetric fraction in parts per million) and a reduction potential or the percent reduction from baseline levels at comparable excess air levels.

4.1 CYCLONES

4.1.1 Low Excess Air

Low excess air is generally considered to be an effective means to reduce NOx emissions, with few detrimental operating effects. However, low excess air operation on cyclone boilers is generally not recommended by their manufacturers due to the possibility of producing air deficient atmospheres in the furnace (Ref. 4-3). The potential creation of a reducing atmosphere in the cyclones may result in severe corrosion problems and eventual tube ruptures. While this danger also exists for other pulverized coal boilers, it is critical in cyclone boilers. In large industrial sized boilers, cyclones operate at fairly low excess air levels. This lower excess air operation leaves little room for further reduction without the fear of corrosion problems.

Data for only one industrial sized cyclone boiler are known. The effect of low excess air on NOx emissions at baseline operation is given in Fig. 4-1. Where there is some scatter in the data, it is apparent that there is only a small effect on NO emissions by reducing the overall O_2 level. On the average, there is only a 30 ppm drop for a 1% change in O_2 level, corresponding to a reduction potential of less than 5%.

One characteristic of cyclone boilers which has been shown to be important in NOx formation is the effect of boiler load (Ref. 4-3). Fig. 4-2 presents the NOx versus load characteristics of this particular boiler. In contrast to similar data for utility boilers, relatively little change in NOx emissions is noted.

4.2 SINGLE-WALL-FIRED BOILERS

4.2.1 Low Excess Air

The use of low excess air for single wall fired industrial boilers operating at base load is shown in Fig. 4-3. In all cases, reduction of the excess air resulted in reduced NO emissions, however, at varying degrees of effectiveness.

The most effective case was for IB-14 rated at 260,000 lb/hr steam. The NOx emissions were reduced by approximately 100 ppm for a 1.1% change in excess O_2. This particular unit also had an unusually high initial NO level, which may, in part, account for the good NO reduction effectiveness. The base NO emission was approximately 960 ppm compared to the 600 and below for the other units. Boiler size is not a factor here, since the largest boiler had lower emissions. This boiler was equipped with a first generation B&W Dual Register burner. These burners can be adjusted for either high NOx, intense flame or low NOx distributed mixing flame. This is probably why the NOx values cover such a large range.

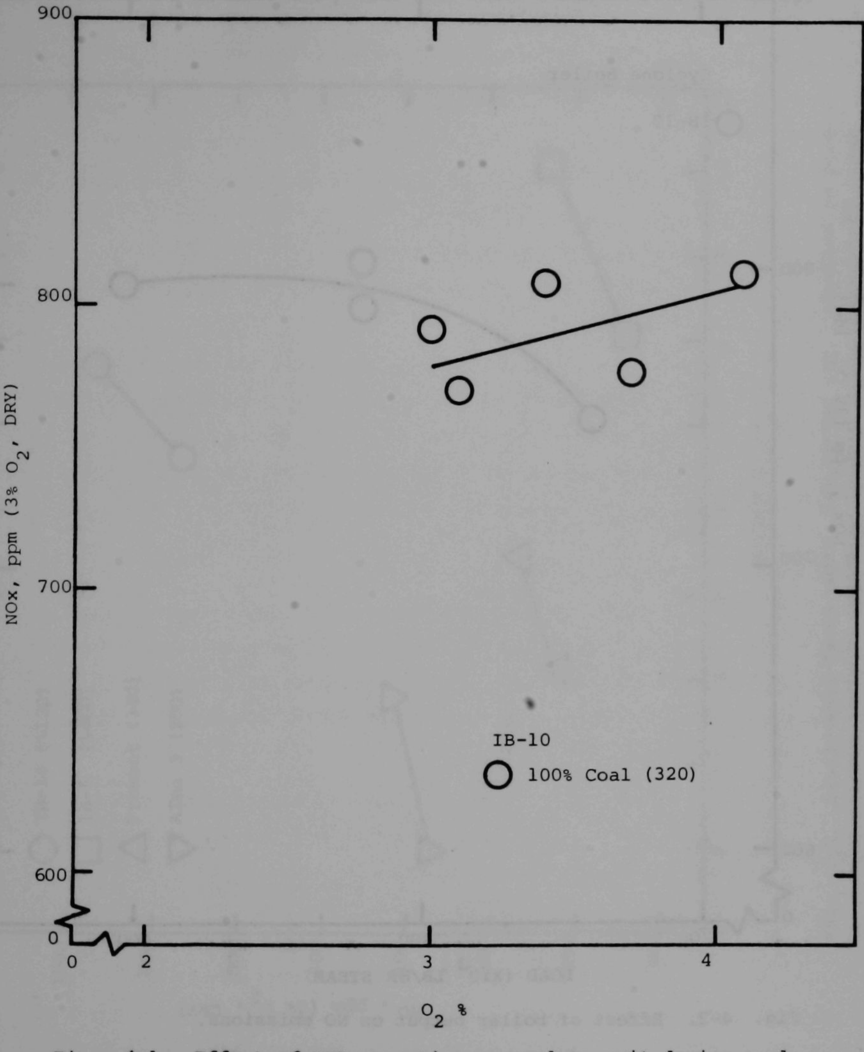


Fig. 4-1. Effect of LEA operation on cyclone unit during coal firing. (Numbers in parentheses indicate operating load in thousand pounds of steam per hour.)

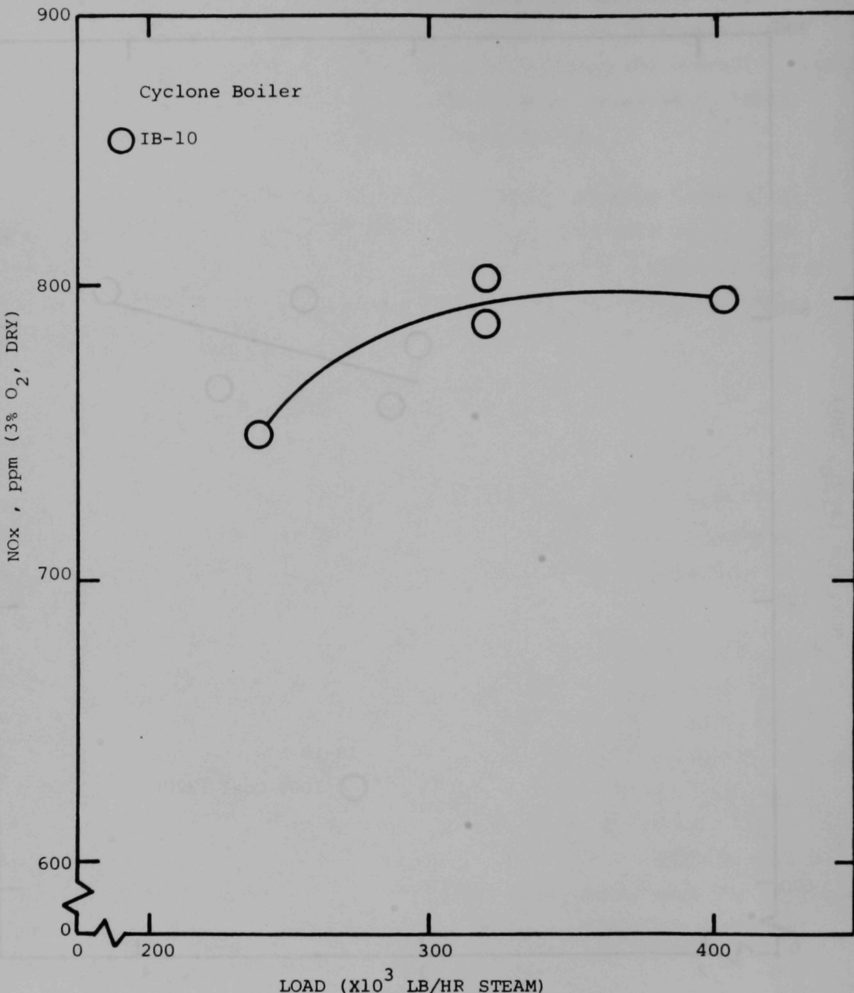


Fig. 4-2. Effect of boiler output on NO emissions.

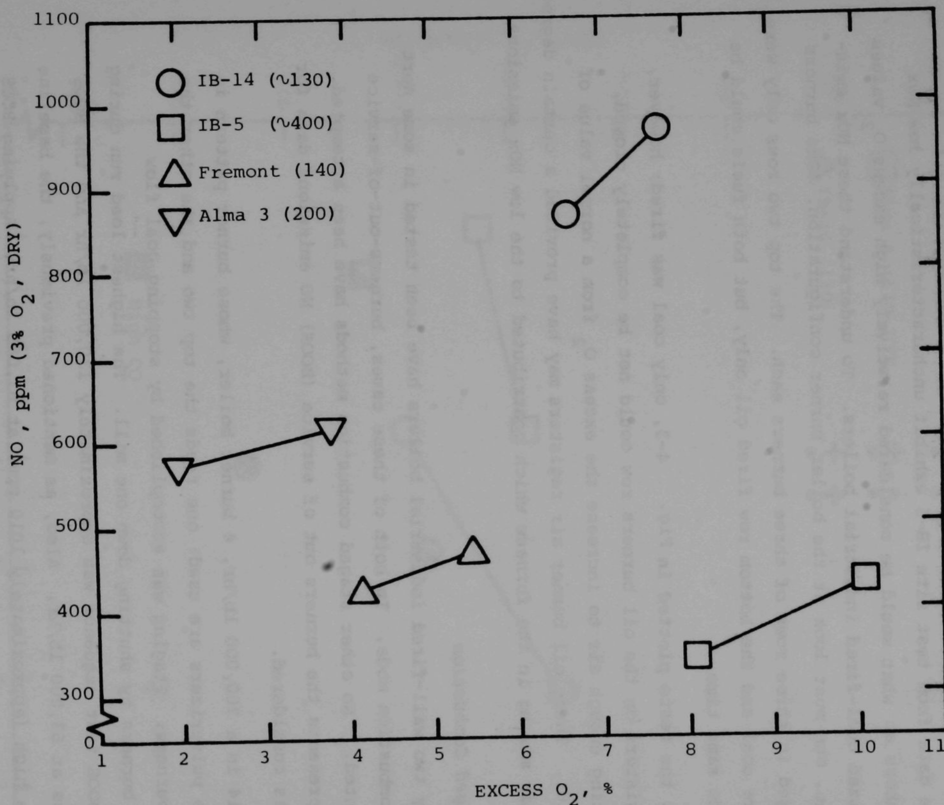


Fig. 4-3. Single-wall-fired units, low excess air. (Numbers in parentheses indicate operating load in thousand pounds of steam per hour.)

For the other boilers, the NO emissions decrease by approximately 35 ppm per 1% decrease in O_2, or roughly 1/3 as effective as the unit described above. Since baseline NO emission levels were three times as high, however, a comparable NOx reduction potential of 5-10% was achieved.

The data from test site IB-5 exhibit uncharacteristically low NOx emission numbers at what would be considered relatively high excess O_2 values for pulverized coal-fired industrial boilers. To understand these NOx emission numbers, one must look at the boiler burner configuration. The burners were arranged in three rows of three burners each. The top two rows only were used to fire coal and the bottom row fired oil only, but both fuels could be fired at the same time.

For the tests plotted in Fig. 4-3, only coal was fired; however, the air registers on the oil burners row could not be completely closed, thus admitting enough air to increase the excess O_2 from a normal value of 4-5% to 8-10%. These oil burner air registers may have provided a certain degree of staged air mixing in the furnace which contributed to the low NOx emissions.

4.2.2 Staged Combustion

Only two wall-fired industrial boilers have been tested in some sort of staged combustion mode. In both of these cases, burners-out-of-service was implemented. No other staged combustion methods have been attempted. Fig. 4-4 presents the burners out of service (BOOS) NO emissions data for the two units considered.

IB-14 is a 260,000 lb/hr, 4 burner boiler, whose burner pattern is square. Two pulverizers are used: one feeds the top two and the other the bottom two burners. Staging was accomplished by stopping coal flow on the top burners by shutting down one mill. The highest load run during the entire BOOS test sequence was approximately 130,000 lb/hr and the BOOS operation was at 63,000 lb/hr. Also, as mentioned previously, the baseline NO level was high (approximately 1010 ppm) at 63,000 lb/hr. Applying BOOS to the top two burners reduced NO emission to 615 ppm, or a 45% reduction with an unacceptable increase in CO emissions. No information was available on flame shape under the different operating conditions.

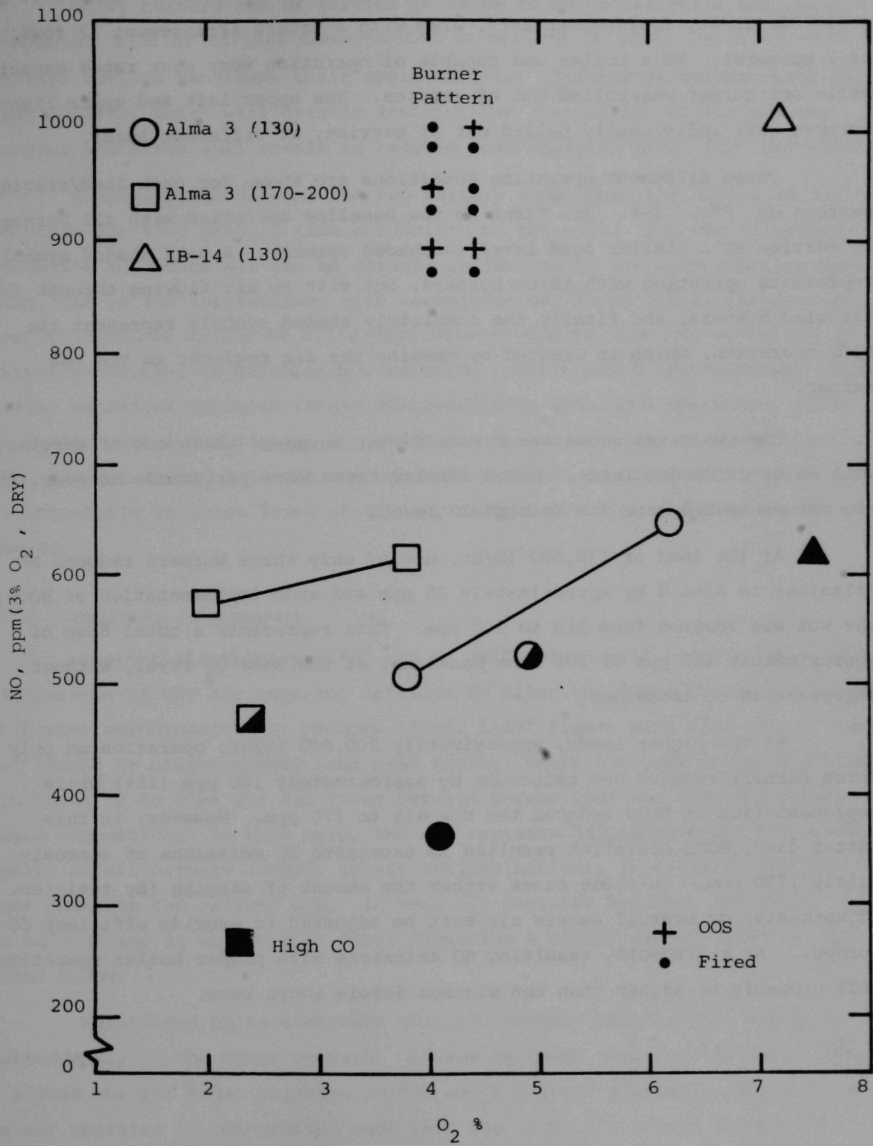


Fig. 4-4. BOOS operation on single-wall-fired pulverized-coal units. All burners in service (open symbol); no air to BOOS (half shaded symbol); and normal air distribution to the BOOS (completely shaded symbol). (Numbers in parentheses indicate operating load in thousand pounds of steam per hour.)

Two different test sequences were conducted at Alma 3. This unit is a 230,000 lb/hr, four-burner unit, also with a square arrangement (2 rows of 2 burners). This boiler was capable of operation very near rated capacity, while one burner was pulled out of service. The upper left and upper right burners were individually pulled out of service, at different loads.

Three different operating conditions are shown for each load/staging pattern on Fig. 4-4. The first is the baseline operation with all burners in service at a similar load level (unshaded symbol). A half shaded symbol represents operation with three burners, but with no air flowing through the disabled burners, and finally the completely shaded symbols represent the BOOS operation, which is created by opening the air register to the one burner.

The two cases shown are for different burners taken out of service, as well as at different loads. Other similar tests were performed; however, these are not presented here due to high CO levels.

At the load of 130,000 lb/hr, use of only three burners reduced NO emissions on Alma 3 by approximately 35 ppm and upon implementation of BOOS, the NOx was lowered from 510 to 360 ppm. This represents a total drop of approximately 150 ppm or 30% from baseline, at the same O_2 level, without increases in CO emissions.

At the higher loads, approximately 200,000 lb/hr, operation on only three burners reduced NOx emissions by approximately 100 ppm (18%) while implementation of BOOS reduced the NOx 47% to 270 ppm. However, in this latter case, BOOS operation resulted in excessive CO emissions of approximately 1770 ppm. In these cases either the amount of staging (by register adjustments) or overall excess air must be adjusted to provide efficient CO burnout. As a tradeoff, resulting NO emissions with proper boiler operation will probably be higher than the minimum levels shown here.

While burners out of service is shown to be successfully implemented in a manner similar to that demonstrated in utility boilers, the small size of industrial boilers handicaps their applicability. Industrial boilers have only a few burners, which will greatly restrict the flexibility of the staging patterns and often will result in reduced load capacity under BOOS operation.

Comparing the data on the two boilers shows that the degree of NOx reduction can vary greatly from one boiler to the next. The use of staged combustion to reduce NOx can be greatly influenced by the burner/boiler geometry, due to the interactions with combustion gas flows within the furnace. A second possible source of difference between the two boilers tested may be the initial unmodified or baseline NOx emission level. The boiler with the higher initial emissions produced larger NOx reduction, with BOOS operation, while the boiler with lower initial NO levels was less effective. In both cases a reduction potential of 30-40% was achieved with 25% of the BOOS. These levels are comparable to those found on utility sized units with the same degree of staging.

4.2.3 Register Adjustments

Another alternative which can be utilized in wall-fired boilers is a modification of the air register settings to alter the flame shapes and control the burner aerodynamics to produce "long, lazy" flames with slow mixing rates. This should be distinguished from bias firing, where the goal of air register adjustment is to bias the air flows between burner rows and thus implement staged combustion. In this case, the air register adjustments are performed equally on all burners (hence, no air redistribution), in order to adjust flame patterns for reduced NOx. In many air register designs, the swirl can be modified at each burner level producing a slowly mixing flame as discussed below.

Wall-fired units generally utilize circular burners that function independently of the other burners. An air register system is normally used to adjust the air flow, relative to the other burners sharing a common windbox. The air register is constructed such that the vanes are near a tangential position at the partially opened setting and at a radial position at a fully opened setting. Besides their use in adjusting the quantity of air, these vanes will also change the flow patterns (swirl) in the local burner region and in the furnace. The local fuel-air mixing process and the recirculation of combustion products from the lower furnace region back into the flame zone are important factors in the resulting flame shape and NOx formation.

By adjusting the registers towards the radial position (wide open) the air flow will contain less swirl; this results in a lower intensity of combustion. This also characteristically produces a longer flame. Pulverized coal burner studies have demonstrated that flames which involve reduced mixing of coal/primary air with secondary air can produce lower NOx emissions (Ref. 4-4).

Register adjustments were performed on all of the burners of Alma 3 and are presented in Fig. 4-5. While operating near 200,000 lb/hr steam, the air registers were adjusted towards the radial position, while the total O_2 levels were held nearly constant. Longer flames were noted in these tests, and lower NOx emissions were achieved. When the registers were held at the radial positions, a slight increase in slagging occurred on the back wall.

Optimizing boilers for lower NOx operation is always dependent upon operational considerations such as slagging, increased water tube temperatures, flame impingement, and reduced efficiency as well as increases in other pollutant emissions (HC, CO).

4.3 TANGENTIALLY FIRED BOILERS

4.3.1 Low Excess Air

Reduced excess air produces a definite reduction in the level of NOx emission on tangentially fired boilers. Fig. 4-6 shows the relationship of excess O_2 versus NO at base loads for three tangentially-fired boilers. In one case, a reduction of 1.8% O_2 lowered NO levels over 130 ppm, or approximately 20%. The other case exhibits an 87 ppm NO reduction corresponding to a reduction in O_2 of 2%.

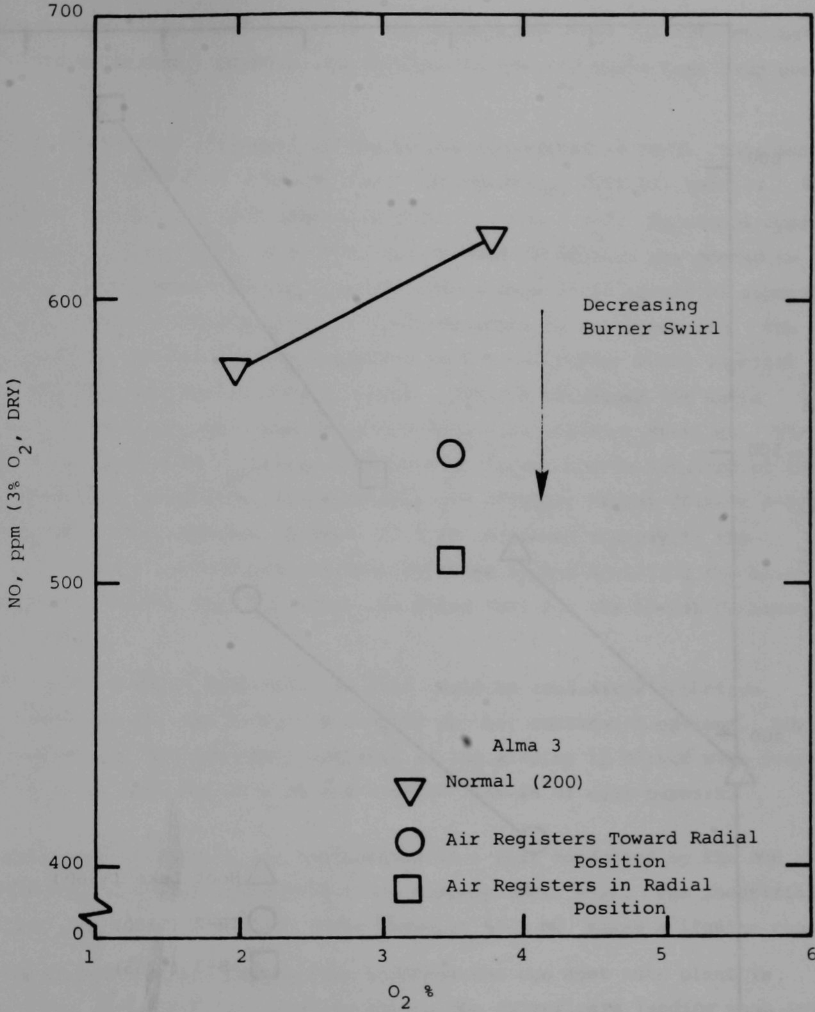


Fig. 4-5. Air register adjustments, single-wall-fired. (Numbers in parentheses indicate operating load in thousand pounds of steam per hour.)

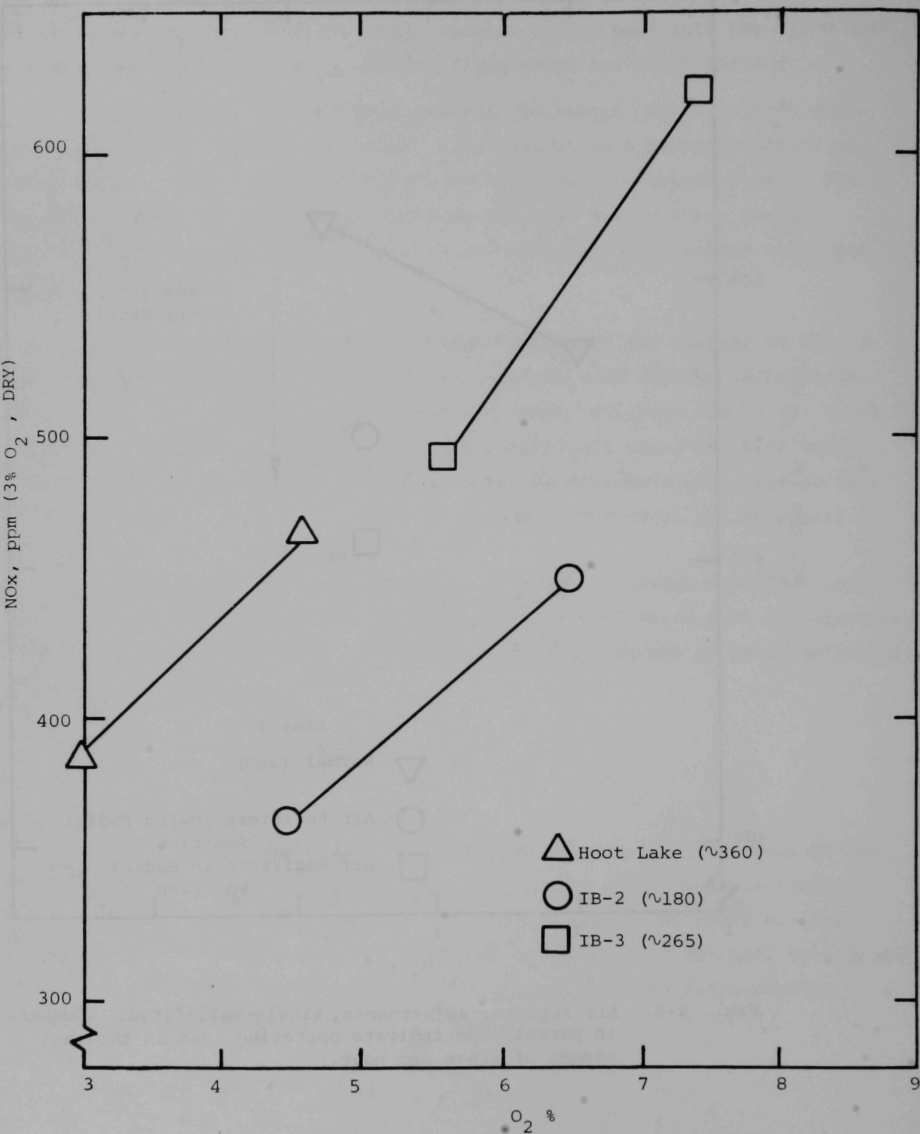


Fig. 4-6. LEA , tangentially fired. (Numbers in parentheses indicate operating load in thousand pounds of steam per hour.)

4.3.2 *Staged Combustion*

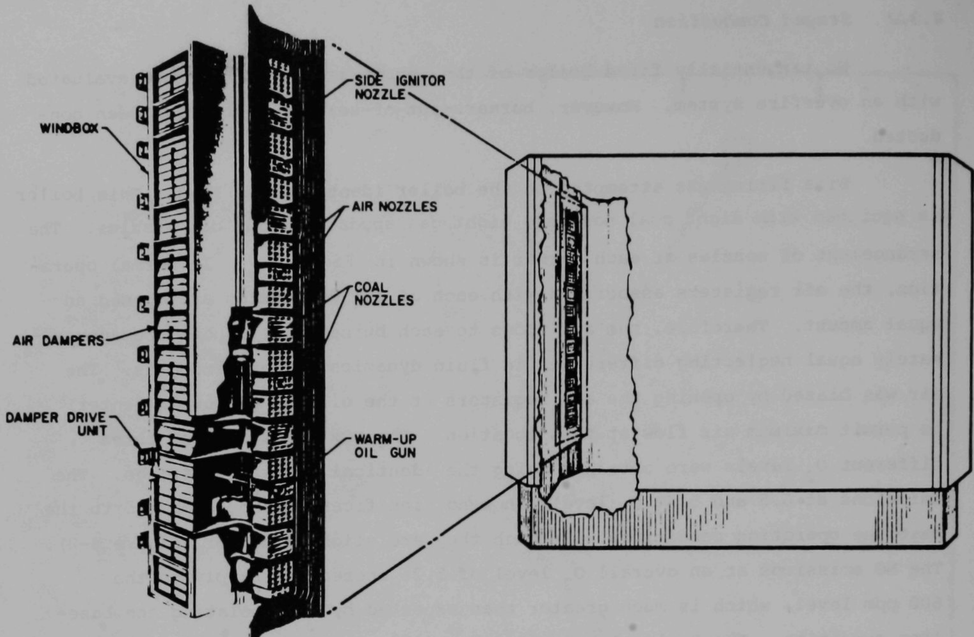
No tangentially fired boiler of the industrial class has been evaluated with an overfire system. However, burners-out-of-service tests have been conducted.

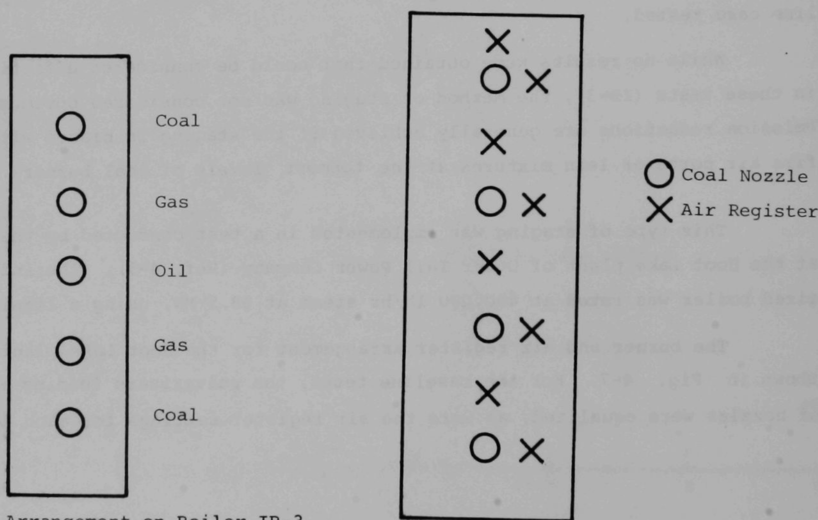
Bias firing was attempted on the boiler identified as IB-3. This boiler is equipped with eight coal nozzles, eight gas spuds and four oil nozzles. The arrangement of nozzles at each corner is shown in Fig. 4-7. In normal operation, the air registers associated with each of the 20 nozzles are opened an equal amount. Therefore, the air flows to each burner level should be approximately equal neglecting differences in fluid dynamics in the windboxes. The air was biased by opening the air registers at the oil burner level (center) to permit maximum air flow at this location. The NOx emissions for three different O_2 levels were obtained using the identical register settings. The emissions at 6.5 and 5.8% O_2 levels show no significant change compared to the baseline operating conditions, although they are slightly higher (Figure 4-8). The NO emissions at an overall O_2 level of 5.2% increased sharply to the 600 ppm level, which is much greater than expected by extrapolating the baseline condition. The O_2 level, however, is below that for the lowest O_2 baseline case tested.

While no results were obtained that could be considered effective in these tests (IB-3), the method of staging was not considered optimum. NOx emission reductions are generally achieved if the staging is biased with overfire air ports or lean mixtures at the topmost levels of coal burners.

This type of staging was implemented in a test conducted by the DOE at the Hoot Lake plant of Otter Tail Power Company (Ref. 4-5). The industrial sized boiler was rated at 400,000 lb/hr steam at 53.5 MW, using a lignite coal.

The burner and air register arrangement for the Hoot Lake plant is shown in Fig. 4-7. For the baseline tests, the pulverizers feeding each level of nozzles were equalized, as were the air register settings for each level.





Burner Arrangement on Boiler IB-3

Burner Arrangement, Hoot Lake

Fig. 4-7. Burner arrangement of IB-3 and Hoot Lake industrial boilers.

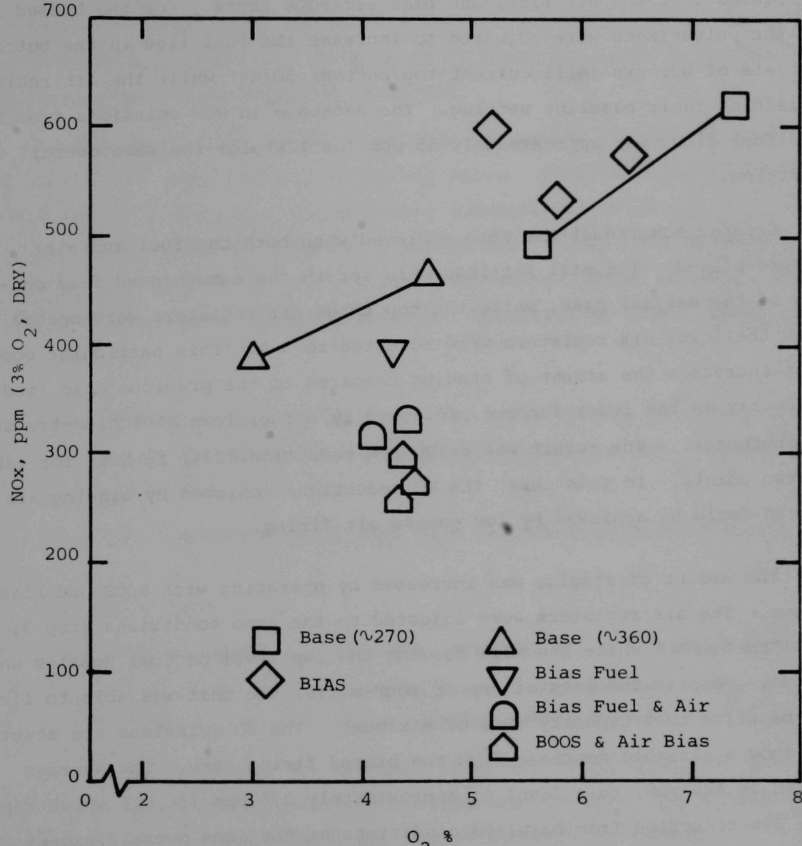


Fig. 4-8. Staged combustion, tangentially fired boiler. (Numbers in parentheses indicate operating load in thousand pounds of steam per hour.)

The air registers between the burners were opened to 40%, while the registers at the level of each burner were set at 100% open. The nozzle tilt controls are used for steam temperature control, and during the baseline tests were left in automatic operation (10-12 degree upward tilt). The majority of the staged combustion tests were run with the nozzle tilt held at zero degrees.

Fig. 4-8 shows the baseline emissions and results using biased fuel flow, biased fuel and air flow, and bias air/BOOS tests. For the biased fuel test, the pulverizers were adjusted to increase the fuel flow in the bottom two levels of burners (mill current top/bottom; 50/64) while the air registers were left at their baseline setting. The decrease in NOx emissions from the biased fuel flows was approximately 55 ppm (or 12%) for the same overall excess air setting.

Greater NOx reductions were achieved when both the fuel and air flows were biased. The mill settings were set in the same biased feed conditions of the earlier case, while the top three air registers were opened to 100% and the lower six registers were adjusted to 50%. This particular combination increases the amount of staging compared to the previous case (reduced stoichiometry in the lower furnace, followed by a fuel lean stoichiometry at the top burners). The result was a 120 ppm reduction (23%) in NOx, for each of the two points. In this case, the NO reductions achieved by biasing are lower than could be achieved by low excess air firing.

The amount of staging was increased by operating with BOOS and biased air flows. The air registers were adjusted to the same conditions (top 3, 100%; bottom 6, 50%) while the mill feeding the top level of coal nozzles was shut down. Despite the loss of one of four mills, the unit was able to fire at the baseline test capacity (90% of maximum). The NO emissions are scattered, but do show a sizeable decrease from the biased firing case. The average reduction is 175 ppm, to a level of approximately 275 ppm (3% O_2) which represents a 39% reduction from baseline conditions at the same overall excess O_2 level.

4.4 STOKER-FIRED BOILERS

4.4.1 Underfed Stokers

NO emissions data as a function of operating excess O_2 for three underfed stokers are presented in Fig. 4-9. Baseline emission levels were approximately 300 ppm in all three cases.

The excess O_2 levels ranged from 4.0 to 10.0% excess O_2. The slope of NO dependence on excess O_2 is similar for all the units tested. NO emissions are reduced about 20 ppm for each 1% decrease in excess O_2 level with an emission reduction potential of about 25%.

In the case of IB-18 and IB-19, the low excess air and baseline points were run on identical but different units. Therefore the "reduction" seen here may be a difference in operating characteristics of the two boilers rather than a true reduction due to an excess air change. The relatively high excess O_2 is due to the small size of the units. These units are 10,000 lb/hr steam single retort underfed stokers. Operation at these excess O_2 levels is normal.

While the reductions of 40-70 ppm for large changes in O_2 level seem small, the baseline emissions for the underfed stokers are low to begin with (approximately 300 ppm).

No staged combustion tests have been performed on an underfed stoker.

4.4.2 Overfed Stokers

The effect of excess air upon NOx emissions for the overfed stokers is presented in Fig. 4-10. One vibrating grate stoker and two traveling grate stokers are represented, with baseline emission levels between 170-280 ppm.

The excess O_2 levels for baseline operation varied from 5.5 to 9.5%. While the degree of effectiveness varied from unit to unit, the average was a reduction of approximately 20-30 ppm per 1% decrease in excess O_2. In the case exhibiting the largest effectiveness (Stout 2) the low O_2 mode resulted in excessive CO emissions.

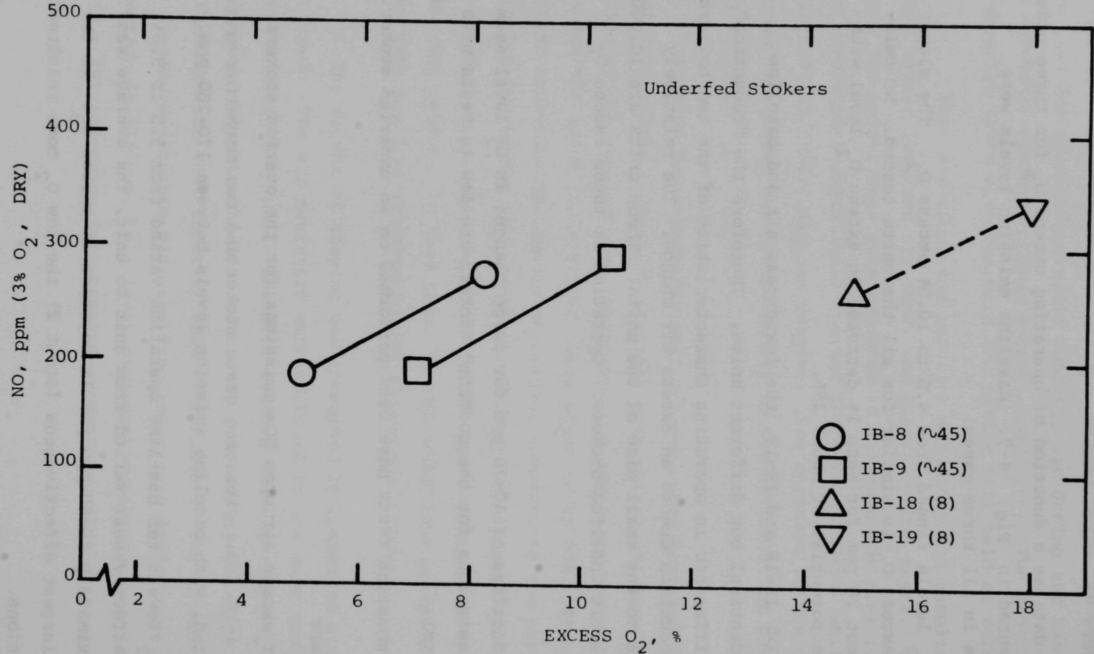


Fig. 4-9. LEA operation on underfed stokers. (Numbers in parentheses indicate operating load in thousand pounds of steam per hour.)

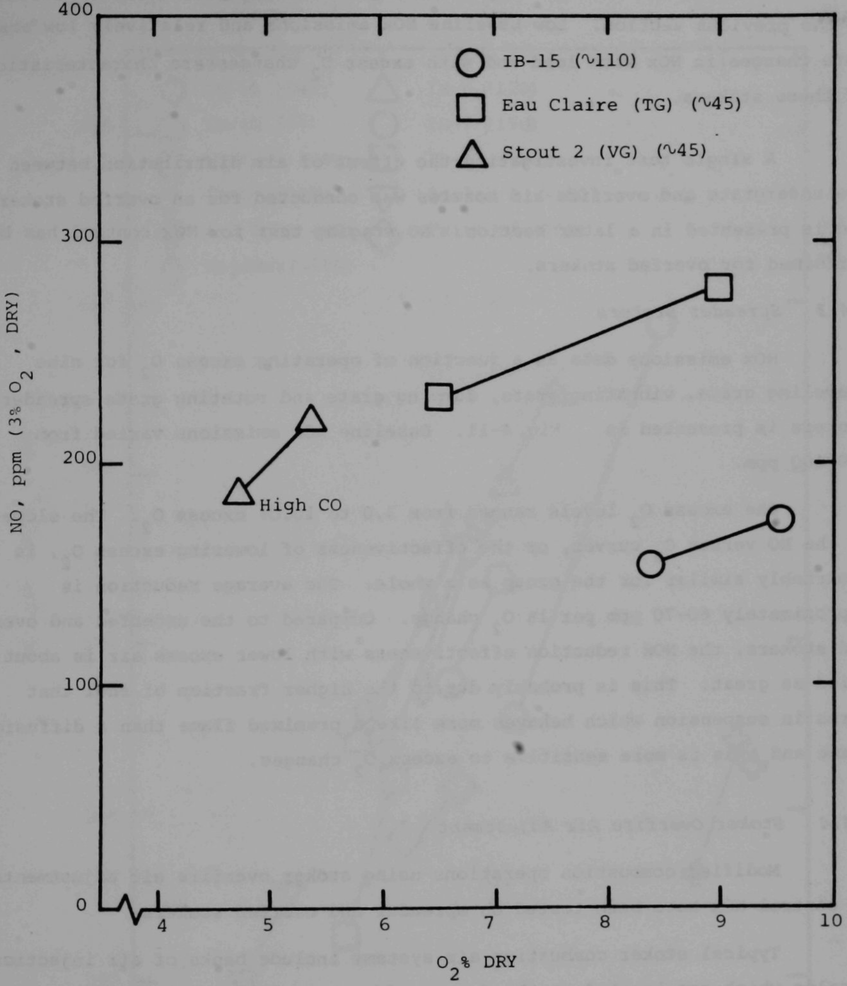


Fig. 4-10. Effect of LEA operation on NO emissions from overfed stokers. (Numbers in parentheses indicate operating load in thousand pounds of steam per hour.)

These boilers behave very similarly to the underfed stokers presented in the previous section. Low baseline NOx emissions and relatively low absolute changes in NOx with load and with excess O_2 changes are characteristic of these stokers.

A single test investigating the effect of air distribution between the undergrate and overfire air nozzles was conducted for an overfed stoker, and is presented in a later section. No staging test for NOx control has been performed for overfed stokers.

4.4.3 Spreader Stokers

NOx emissions data as a function of operating excess O_2 for nine traveling grate, vibrating grate, dumping grate and rotating grate spreader stokers is presented in Fig. 4-11. Baseline NOx emissions varied from 300-600 ppm.

The excess O_2 levels ranged from 3.0 to 10.0% excess O_2. The slope of the NO versus O_2 curves, or the effectiveness of lowering excess O_2, is remarkably similar for the group as a whole. The average reduction is approximately 60-70 ppm per 1% O_2 change. Compared to the underfed and overfed stokers, the NOx reduction effectiveness with lower excess air is about twice as great. This is probably due to the higher fraction of fuel that burns in suspension which behaves more like a premixed flame than a diffusion flame and this is more sensitive to excess O_2 changes.

4.4.4 Stoker Overfire Air Adjustment

Modified combustion operations using stoker overfire air adjustments to control NOx have been tested on spreader and overfed stokers.

Typical stoker combustion air systems include banks of air injection nozzles which are located at the front and/or rear walls of the furnace just above the fuel bed. These nozzles utilize approximately 5-10% of the combustion air in order to promote turbulent mixing over the fuel bed and enhance CO burnout. While this air injection system is accurately described as overfire

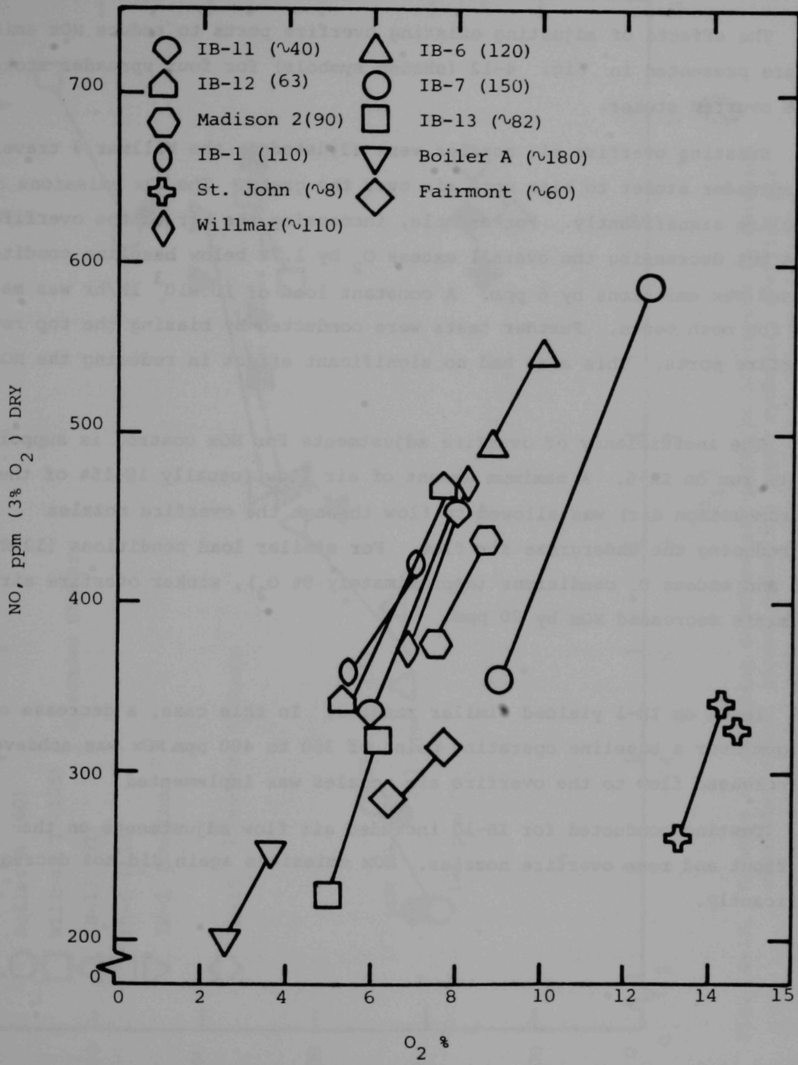


Fig.4-11. Effect of excess O_2 on NO emissions, spreader-stoker units. (Numbers in parentheses indicate operating load in thousand pounds of steam per hour.)

air nozzles, their purpose is quite unlike overfire air injection ports used for NOx control in utility sized boilers.

The effects of adjusting existing overfire ports to reduce NOx emissions are presented in Fig. 4-12 (shaded symbols) for four spreader stokers and one overfed stoker.

Existing overfire air nozzles were adjusted on the Willmar 3 traveling grate spreader stoker to bias more air over the grate. The NOx emissions did not decline significantly. For example, increasing the air to the overfire nozzles but decreasing the overall excess O_2 by 1.7% below baseline conditions decreased NOx emissions by 6 ppm. A constant load of $105x10^3$ lb/hr was maintained for both tests. Further tests were conducted by biasing the top row of overfire ports. This also had no significant effect in reducing the NOx levels.

The inefficiency of overfire adjustments for NOx control is supported by tests run on IB-6. A maximum amount of air flow (usually 10-15% of the total combustion air) was allowed to flow through the overfire nozzles while reducing the undergrate air flow. For similar load conditions ($120x10^3$ lb/hr) and excess O_2 conditions (approximately 9% O_2), stoker overfire air adjustments decreased NOx by 20 ppm.

Tests on IB-1 yielded similar results. In this case, a decrease of 20-30 ppm over a baseline operating point of 350 to 400 ppm NOx was achieved when increased flow to the overfire air nozzles was implemented.

Testing conducted for IB-13 included air flow adjustments on the upper front and rear overfire nozzles. NOx emissions again did not decrease significantly.

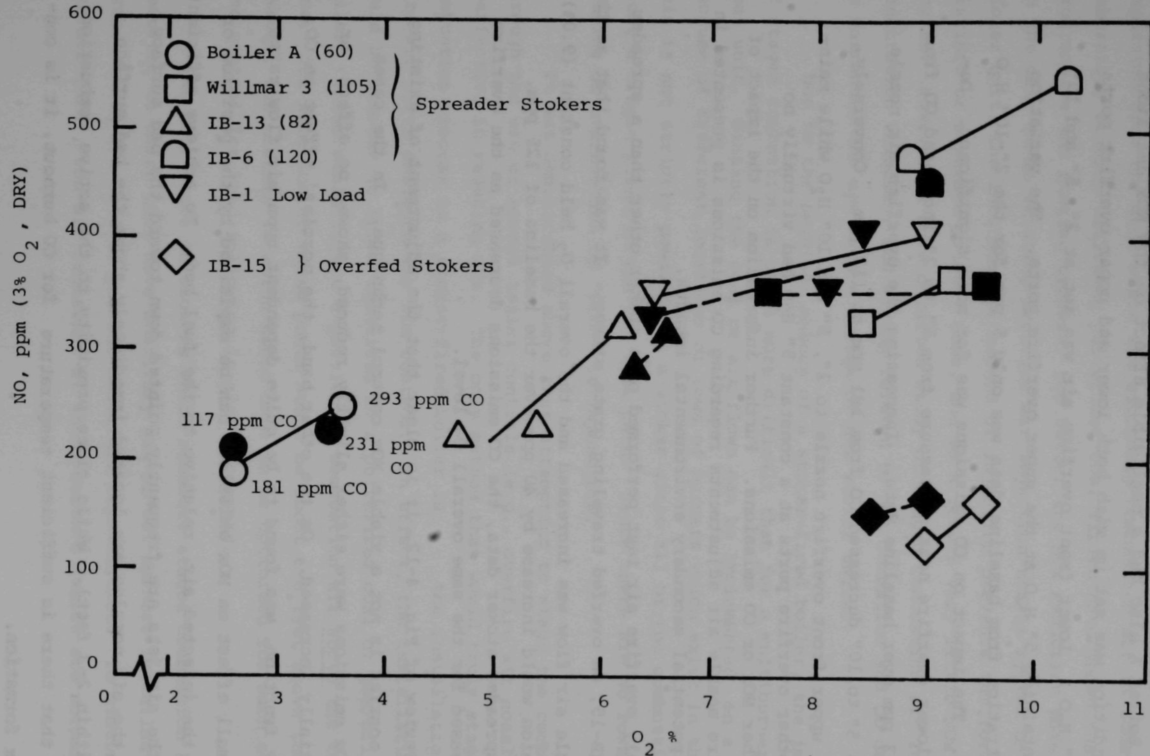


Fig. 4-12. Effects of adjusting overfire-air ports on NO versus O_2 emission characteristics, normal operation (open symbols); overfire air adjusted (shaded symbols). (Numbers in parentheses indicate operating load in thousand pounds of steam per hour.)

The effect of adjusting overfire air pressure on lower and upper banks of nozzles on Boiler A also had a negligible effect on the NOx emissions. A baseline condition was set up with both lower and upper overfire ports adjusted to 5" H_2O . Lower front overfire air was set at 2", 5" and 10" H_2O while maintaining 5" H_2O at the upper overfire ports. The variation of NOx concentration from baseline data was only 5 ppm for the 2"-10" H_2O range studied. The impact on CO emissions was far more significant. Decreasing the lower overfire nozzle pressure from 5" to 2" increased CO from 181 ppm to 293 ppm over baseline data. Increasing the overfire air nozzle pressure from 5" to 10" decreased CO from 181 ppm to 117 ppm. Conversely, adjusting the upper front overfire nozzle to 2", 5" and 10" H_2O while maintaining the other overfire ports at a constant 5" H_2O had virtually no impact on either NOx or CO emissions. Further information on the impact of stoker overfire nozzle air adjustments regarding CO emissions is presented in a section on potential secondary environmental impacts.

The only overfire air test performed on a stoker other than a spreader was the test of IB-15, an overfed traveling grate stoker. It was found that as the overfire nozzle air flow was increased and the overall O_2 held constant (9.0%), the NOx emission would increase by 40 ppm over the baseline of 125 ppm. As with the spreader stoker data, the CO emissions decreased as the overfire air was increased for the same overall O_2 level.

Upon review of Fig. 4-12, it is clear that the adjustment of existing overfire air nozzles is not a viable NOx control technique. In the cases shown, the NOx emissions were either slightly reduced, showed no effect, or were substantially increased. On the other hand, the nozzles' effect on CO, their primary function, was found to be quite dependent upon air flow rates.

The small effect on NOx emissions can be explained by the position or flow path of the injected air relative to the fuel bed. To achieve efficient CO burnout, the air jets are frequently pointed down toward the bed surface. Furthermore, the air nozzles are located immediately above the bed surface (generally within 2-3 feet). While close proximity to the active combustion zone insures that there is sufficient temperature for CO burnout, it is conducive to NOx formation.

The use of staged combustion air relies upon the creation of a primary combustion zone that is either near stoichiometric or fuel-rich and is separated from the zone where the secondary combustion air is added. Various laboratory studies utilizing pulverized coal firing have shown that the more progressive the staging process, the better the NOx reduction potential. In the case of an existing overfire air injection nozzle system on a typical stoker unit, the location and method of injection prevents the formation of a distinct or separate primary zone, and as a result very little NOx reduction occurs. However, a more detailed study of staged combustion air location, penetration velocity, and mixing related to NOx formation and CO destruction is warranted for use in the design of new stoker units.

Due to the physical makeup of a stoker-fired boiler, the implementation of staged combustion is often more difficult than for a multiburner pulverized coal unit. Biasing the coal or air flows can be implemented on a PC boiler because of different locations or rows of burners which exist in the furnace. This is not strictly possible in a stoker since all of the combustion occurs along a single plane in the air flow path. Since there are no rows of stokers, biasing or utilization of "BOOS" is impossible.

It was demonstrated above that attempting to stage the combustion through the use of normal boiler controls (e.g., overfire air nozzles) was ineffective in reducing NOx. The only method that would truly stage the combustion process in a stoker-fired boiler is the installation of overfire air ports designed for NOx control. In effect, the installation of ports would be similar to those installed in a pulverized coal or gas/oil fired boiler. These would inject a portion of combustion air above the combustion zone. The location of these ports would be about 6-8 feet above the grate; however, the precise location would have to be optimized for each stoker. Some control for load following is also necessary.

The only tests on stokers which simulate staged combustion have been conducted on units that have auxiliary gas or oil burners installed in the furnace which are used to provide multifuel capabilities. To simulate overfire air (OFA), the air registers of these burners (which are normally closed under coal-fired operation) were opened to inject additional air. These data indicate that staged combustion through the use of inactive gas/ oil burners, or installation of OFA ports may be a viable method in reducing NOx emissions in stokers. Particularly in new units where the uncertainty in future fuel supplies exists, multifuel capability becomes an attractive feature. Fig. 4-13 presents the three cases where staged combustion was performed. All three boilers tested were of the spreader stoker type.

IB-6 is a spreader stoker utilizing 5 spreaders, with a baseload of 120,000 lb/hr steam. The boiler was equipped to fire gas and oil through two burners, one located on each of the two side walls. Under normal operation, the air registers of the burners were set at a 10% open position. To simulate OFA firing, these air registers were adjusted to a 30% open position, which diverts a greater proportion of air from the under grate through the burner. The test results showed an emission of 475 ppm NOx accompanied by an increase in excess O_2. This operating point was soon abandoned due to the formation of a layer of fused coal on the grate (clinker). Apparently, so much air had been diverted from under the grate that clinkers were forming. No other staged air tests were performed on this unit. Clinkering would have been even more severe had the overall excess O_2 level been maintained at the baseline condition.

Boiler IB-7 was also a spreader stoker with six spreaders and a baseline capacity of approximately 160,000 lb/hr. Like IB-6, two gas/oil burners were located on each of the furnace side walls, but under normal operation, their registers were closed. These registers were opened to the 20% position and the control for the overfire air was reduced to 50% (from the normal 100% setting). As can be seen in Fig. 4-13, there is no definite trend in NO emission versus O_2 level for the staged combustion case. This is not surprising since for staged operation one would expect the air/fuel ratio in the primary combustion zone to be the primary factor in determining the NOx emission levels. Unfortunately, this parameter was not determined for these tests. Also for three cases shown, the NOx emission is lower for a given over-all excess O_2 level (90 ppm in one case). However, none shows a significant

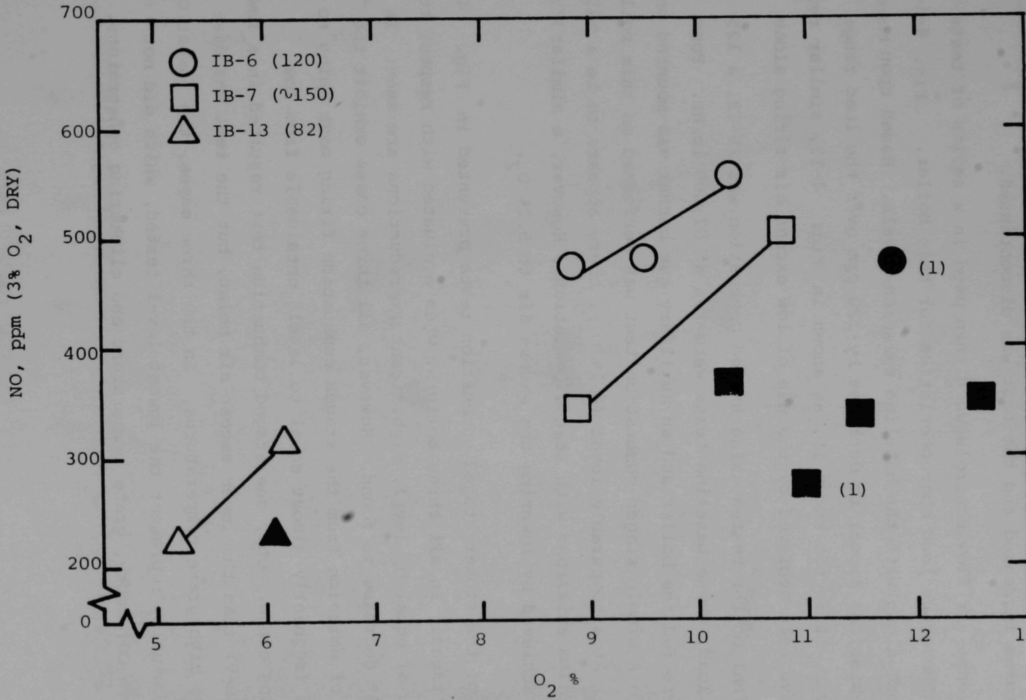


Fig. 4-13. Staged combustion on coal-fired spreader stoker units using OFA operation through out-of-service auxiliary burners. Baseline (open symbols), and staged conditions (shaded symbols); (1) - high CO emission. (Numbers in parentheses indicate operating load in thousand pounds of steam per hour.)

reduction compared to the low excess air operation. Only one short term test showed a significant reduction of NOx emission compared to the low excess air point (a 70 ppm decrease.) While the coal was reportedly burning adequately, grate temperatures increased and the test was discontinued.

These same air flow controls were then used in a series of tests to determine the NOx versus load characteristics for this boiler. Fig. 4-14 shows this trend along with the baseline emission levels. Based upon these data, the NOx emissions appear to decrease by 120 ppm over the load range tested. However, it is not known if, as shown in Fig. 4-13, similar reductions could have been achieved by the use of low excess air firing alone.

The final boiler tested using staged combustion was IB-13, a 125 lb/hr maximum load, whose baseline tests were run at 82,000 lb/hr. Four spreader stokers fed the boiler and an auxiliary gas burner was mounted on one side wall. A single staged combustion test was performed on this boiler (Fig. 4-13). At a comparable level (6.1% O_2), there appears to be a $\sim$75 ppm decrease in NOx emissions with staged operation. However, a similar NOx reduction was achieved by lowering the excess air to 5.2% O_2.

Review of the stoker staged combustion tests presented in Fig. 4-14 shows a common trend. In all three boilers, when evaluated with respect to baseline points of equal O_2 level, significant NOx reductions are seen. In some cases a 20% decrease is found. However, all three cases exhibit the characteristic of emission from the staged combustion firing mode being no lower than, and frequently almost equal to levels obtainable from low excess air firing alone. Only one staged combustion test resulted in a lower NOx emission (IB-7) than the lower excess air point, but the test was discontinued due to high grate temperatures. In the three cases, the lowest O_2 baseline points usually represent the lowest level tested, which did not exhibit excessive CO, smoke, grate temperature and clinkering constraints.

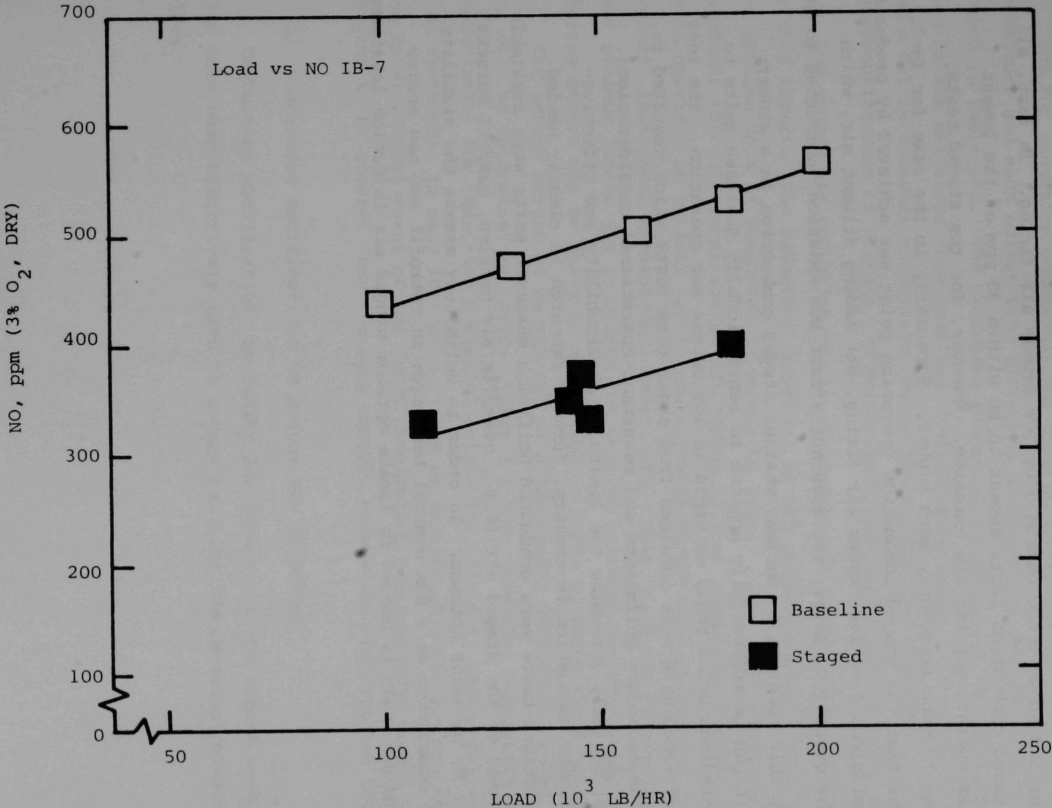


Fig. 4-14. Effect of load on NOx emissions, baseline and staged conditions on 160,000 lb/hr spreader-stoker using auxiliary burners.

At this time, the data presented from the very limited testing of staged combustion of stoker fired boilers have shown no reduction in NOx emissions over and above those obtained by low excess air firing. In fact, all of the staged combustion tests appear to be within 30 ppm of the lowest excess air operating point NOx emission. However, for the staged tests, the O_2 levels were frequently much higher. Especially in the case for IB-7, it appears that the staged combustion operating point was achieved by producing the NO emissions from low excess air firing, but adding diluent air, which raises the overall O_2 level, yet does not affect NOx emission (corrected to 3% O_2).

At this point it is unclear whether staged combustion in a stoker-fired unit can be successfully applied to conventionally designed units to reduce emissions below those obtained in low excess air operation. The test points presented here were obtained from short term tests which resulted in few data on secondary pollutants and resultant operational considerations. Therefore, to fully determine the limits of applicability and effectiveness of staged combustion in stokers, further research is clearly needed. Also, the staged tests were conducted utilizing whatever ports were available for injection of the staged air (e.g., overfire air nozzles, gas/oil burners) which were by no means optimum. In order to definitely assess the viability of staged combustion as a NOx control technique in retrofit and new stoker units, further study is needed to locate optimum staged air injection locations.

4.5 SUMMARY OF NOx-REDUCTION POTENTIAL

The NOx reduction potentials for each of the combustion modification techniques and each boiler type discussed in the previous sections are presented in Table 4-1. The reduction potential is defined as the percent reduction in NOx emissions from baseline conditions at comparable excess O_2 levels. Table 4-1 is somewhat incomplete due to the limited data available and the inappropriateness of certain combustion modifications/unit type combinations.

Low excess air operation can be applied to all boiler types discussed in this report. The reduction potential of LEA operation presented in Table 4-1 applies to a 1% reduction in excess O_2 level. This does not always represent the full potential of LEA firing in that industrial boilers tend to be operated at various levels above practical minimums because of operator neglect, instrument limitations, habit, etc. Some units may be operated at near minimum levels (as is common for utility boilers) for efficiency reasons whereas others may be operated at as high as 5-10% O_2 above the minimum excess O_2. The actual margin of excess air on a particular unit with a given coal can only be determined by tests. Table 4-1 does show that comparable (and appreciable) NOx reduction potential exists for all units considered other than cyclones. In many instances, tests on industrial sized boilers showed the total effectiveness of LEA (when considering the available excess O_2 margin) to be greater than the more complex combustion modification techniques.

4.5.1 Combustion Modifications to Reduce NOx Emissions

Combustion modifications including low excess air and staged combustion have been effectively used to reduce baseline NOx emission concentrations.

Table 4-1. Summary of NOx-Reduction Potential

Firing Type	LEA	Air Register Adjustment	BOOS	Simulated OFA: Injection Systems	Simulated OFA: Auxiliary Burners	Bias
Suspension Firing						
Cyclone	5%	-	-	-	-	-
Single Wall	5-10%	15%	30-45%	-	-	-
Tangential	10%	-	40%	-	-	12-25%
Stokers						
Underfed	10%	N/A	N/A	-	-	N/A[a]
Overfed	10%	N/A	N/A	0-20%	-	N/A
Spreader	10-15%	N/A	N/A	0-5%	10-20%	N/A

[a]N/A = not applicable

Low excess air (LEA) involves operating the boiler with a reduced amount of overall excess air. Minimum excess air levels are determined by unsatisfactory operating conditions. Industrial boilers tend to be operated at various levels (0 to 5% excess O_2) above practical minimums due to improper air or fuel distribution, instrument limitations, operator neglect, etc. The reduction potentials presented in Table 4-1 apply to a 1% reduction in excess O_2 level. In many instances, the actual reduction potential of LEA (considering the margin in excess O_2) was greater than the more complex staging techniques.

Burner air register adjustment to reduce the flame swirl and produce longer, slower mixing flames was attempted on a single wall-fired unit. This procedure was shown to reduce NOx emissions by 15%.

Staging the combustion process into primary and secondary combustion regions can be achieved through burner-out-of-service (BOOS) and overfire air (OFA) operation. These techniques are very effective in reducing NOx emissions by reducing the availability of oxygen in the primary combustion zones. The application and reduction potential of these techniques are highly dependent on the location and flexibility of the unit's coal and air supply to the furnace.

BOOS is implemented by terminating the flow of coal to selected burners (and thereby increasing coal flow to the remaining burners) while maintaining air flow through all burners. In this manner, sufficient segregation of fuel-rich and air-rich zones is created to influence NOx formation. The reduction potential of BOOS is dependent on the degree of staging (percent of BOOS) which is severely limited on industrial sized units by the few burners involved. Reduction potentials presented in Table 4-1 represent operation with 25% of the BOOS and reduced loads. These reduction potentials are comparable to the results from utility sized units with the same degree of staging (Ref. 4-1). The widespread application of BOOS to industrial units is questionable due to load restrictions unless modifications to burner systems are made.

OFA operation has been simulated on stoker units using both existing overfire air injection systems (installed for increased turbulence in the volatile combustion regions directly above the bed) and through the air supply systems for auxiliary, wall mounted burners. As given in Table 4-1, the use of overfire air injection systems has been shown to have little effect on reducing NOx emission and, in fact, increased emissions on an overfed stoker. Use of auxiliary burners, however, reduced NOx emission levels by 10 to 20%. These data indicate that optimum design of OFA ports for NOx control could show significant reduction potentials on stoker units. Although data on an industrial sized suspension fired unit equipped with OFA ports was not available, the results from utility boiler tests showed reduction potentials of 15% and 30% for single wall and tangentially-fired units, respectively.

Biased firing of both air and coal flows was conducted on a tangentially fired unit with a resulting reduction potential of 12-25%. For this unit, the NOx reductions achieved by bias firing were lower than could be achieved by LEA.

The data presented in this section were compiled from field test programs conducted by KVB under sponsorship of the EPA and DOE (Refs. 4-6,7,8,9). For the most part, the reduction potentials presented in Table 4-1 pertain to conditions at one local point for short duration tests under steady operation conditions. Examination of these combustion modifications under fluctuating or reduced load conditions over extended periods must be made prior to their full implementation as routine operating procedures.

REFERENCES FOR SECTION 4

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4-5 Horea, F. I., et al., *The Effects of Overfire Air and Low Excess Air on NOx Emissions and Ash Fouling Potential for a Lignite-Fired Boiler,* presented at American Power Conference (April 1978).

4-6 Cato, G. A., et al., *Field Testing: Application of Combustion Modifications to Control Pollutant Emissions from Industrial Boilers - Phase I,* EPA 650/2-74-078a (October 1974).

4-7 Cato, G. A., et al., *Field Testing: Application of Combustion Modifications to Control Pollutant Emissions from Industrial Boilers - Phase II,* EPA 600/2-76-086-a (April 1976).

4-8 Maloney, K. L., *Systems Evaluation of the Use of Low Sulfur Western Coal in Existing Small and Intermediate Sized Boilers,* EPA Contract 68-02-1863 (unpublished information).

4-9 Gabrielson, J. E., et al., *A Testing Program to Update Equipment Specifications and Design Criteria for Stoker-Fired Boilers,* DOE/EPA Contract EF-77-C-01-2609 (unpublished information).

5 OPERATIONAL CONSIDERATIONS

This section will identify the more important design, operational and maintenance factors involved in the implementation of low NOx combustion modifications and their resultant impact. The types of combustion modifications covered will include low excess air firing, the different forms of staged combustion, and burner/stoker/air register adjustments. Consideration of energy penalties, applicability to a particular boiler design, operational problems, maintenance, effects on auxiliary equipment and secondary pollution emissions will be discussed.

Because of the wide variation in the types of boiler included in the category of industrial boilers, the section will be divided into a discussion concerning pulverized coal and stoker-fired units. The problems involved for pulverized units are largely the same as those for the utility boiler systems, and therefore much of the information presented in Ref. 5-1 is applicable and will be stressed. This report will emphasize specific limitations due to the smaller size of the pulverized coal industrial boilers. Similarly, discussions devoted to stoker operation will stress those areas of importance resulting from different combustion methods, construction and operation.

The operational factors mentioned previously will be grouped into four major topic areas:

1. Problems in design, implementation, operation, and maintenance of a NOx control technique (e.g., corrosion, erosion, combustion stability, heat transfer, combustion controls, new and retrofit applications, etc.).

2. Possible energy benefits or penalties associated with the implementation of a given NOx control method.

3. Impact of low NOx modes on other pollutants (e.g., CO, HC, particulates, POM's, etc.) and on the performance of auxiliary equipment (e.g., electrostatic precipitators, SO_2 scrubbers, auxiliary power consumption, etc.).

4. Cost of combustion modifications including initial implementation and annual costs.

The implementation of low excess air (LEA) and staged combustion operations is attractive compared to other NOx control methods since it frequently can be accomplished with few or no hardware modifications. For these reasons, it can be a cost-effective retrofit application and often can be incorporated in new unit designs for little incremental capital cost.

One of the main considerations in implementing a LEA or staged combustion operating mode is the requirement that the boiler be in good operating condition and that a systematic preventative maintenance program be applied to preserve this operating condition. This requirement is primarily concerned with the coal and air handling equipment, burners, and combustion control equipment that are essential to maintaining close control of local and overall air/fuel ratios.

One of the attributes of low excess air operation is the improved boiler efficiency and reduced fuel consumption that accompanies this operating mode. This is accomplished through a reduction in stack dry gas losses. Lower excess air means less excess air heated to stack exit temperatures. Although an efficiency gain does not result from staged combustion, it frequently can be implemented with little or no loss in boiler efficiency.

LEA or staged combustion can be effectively implemented if particular attention is paid to establishing a suitable long term operating condition without smoke, slagging or fouling, or combustible losses. The major long term consideration that is important to boiler life is possible water tube wall corrosion due to reducing environments created by fuel-rich operation in the lower furnace region.

In the following sections, each of the four major topics listed above will be discussed individually. An overview of each area will be presented followed by more detailed discussion pertaining to the pulverized and stoker-fired units.

5.1 PROBLEMS IN DESIGN, INSTALLATION, OPERATION AND MAINTENANCE -- NEW UNITS AND RETROFIT

5.1.1 Design

Several factors must be considered in the design of a coal-fired unit for low excess air operation and staged combustion. These include (but are not limited to):

(a) adequate pulverizer or mill capacity to permit biased firing or burners out-of-service operation without a reduction in load capacity, i.e., sufficient to permit mill maintenance outage or poor coal operation without load reduction

(b) proper placement and design of mills and coal pipes to insure even coal distribution to the individual burners

(c) mill and burner arrangement to provide flexibility in establishing desirable staging patterns

(d) adequate forced draft fan capacity and level-by-level or individual burner combustion air control (with flow indicators) to insure uniform air flow distribution to burners

(e) adequate furnace volume and convective section design to permit biased firing or staged combustion while meeting steam temperature requirements and with acceptable carbon carryover

(f) burner spacing and flame interaction to permit fuel-rich operation while achieving adequate burnout

(g) proper design of overfire air ports with appropriate spacing relative to burners and injection velocity to accomplish secondary combustion but without significant NO formation

(h) advanced combustion controls with proper placement of an adequate number of oxygen sensors to determine combustion conditions in the burner region, i.e., sensors placed to avoid leakage, air from BOOS or overfire ports, and uncharacteristic recirculated flows

(i) burner or furnace designs to minimize extensive contact of fuel-rich combustion zones with boiler tube walls in the furnace region (temperature and gas composition instrumentation to indicate operating conditions in lower furnace regions)

(j) conservative tube spacings to minimize pressure drop and fouling problems and larger number of properly placed furnace blowers to minimize slagging problems

(k) improved flame scanner and combustible monitors for start-up and modified operating modes

(l) proper windbox and furnace design to avoid acoustic resonant vibration and "rumble"

(m) burner logic and flame scanner system designs that permit the convenient implementation of burner-out-of-service patterns

Although the factors listed above may at first glance appear to be quite extensive in number, many of the considerations are part of normal good boiler design practice, with or without low NOx operating modes. The most satisfactory operation will be achieved by utilizing the latest refinements in boiler design and combustion technology. For new units, most of the recommendations listed concern design improvements that can often be incorporated for the cost of only the engineering design effort with minimal increased material or fabrication costs.

Since NOx control technology on coal-fired units is still under development, one could argue that adequate design technology does not exist, particularly concerning the scaling of burners, combustion zones, and burner interactions.

It is clear that these factors are most applicable to large pulverized coal-fired industrial and utility boilers, especially with respect to pulverized fuel distribution systems, burner spacing, combustion controls and monitoring systems. Most of these factors are of little concern to stoker-fired boilers. For example, the implementation of staged combustion utilizing burners out of service has no application in stoker firing. In contrast, those ideas concerning accurate combustion air flow control, or furnace and boiler design considerations are important to all design types.

One of the main differences between the smaller pulverized-coal and the majority of stoker-fired industrial boilers is in the design of combustion monitoring and control equipment. Often these units may not have an on-line, continuous excess oxygen analyzer, much less a sophisticated flame scanner system. The presence of an O_2 analyzer is of critical importance in the monitoring and application of low excess air or staged combustion because it serves as a check against unsafe, fuel-rich operating conditions as well as being an indicator of the low excess air combustion condition. For small units, especially units below 50,000 lb/hr, instrumentation for combustion monitoring is usually absent and the operators rely on visual observations to make adjustments. Larger units (>200,000 lb/hr steam) will generally include excess air instrumentation, since consideration is given to boiler efficiency and protection systems. On smaller units, before combustion modifications can be implemented, an excess O_2 monitoring system must be installed. On new boiler installations, serious consideration should be given to the acquisition of an O_2 monitoring system for future implementation of combustion modifications and efficient boiler operations. A carbon monoxide monitor would also be worthwhile as a safety feature to insure against incomplete combustion that could be brought on by changing coal composition (e.g., moisture content).

On the utility boiler scale, NOx control technology for coal-fired boilers is still under development; however, a serious limitation exists for the industrial boiler class. Most prior studies have been oriented toward application in utility, pulverized coal-fired systems, especially with regard to meeting current or future regulations. It has been pointed out that more research is needed in the area of scaling the combustion process from research to full sized units, as well as additional fundamental research into the fuel nitrogen conversion process. There has been a serious lack of studies which have addressed NOx reduction on stoker-fired boilers. While some products developed for the utility boiler application can be utilized in the large industrial boilers (e.g., low NOx burners), no alternatives exist for stokers. Obviously, much of the response to low NOx burner and boiler development has been due to the implementation of federal and local NOx regulations applied to the utility boilers.

5.1.2 *Implementation and Operation*

The implementation and operation of a low excess air or staged combustion operating mode is concerned primarily with boiler adjustments and monitoring to insure that satisfactory combustion conditions have been achieved. The discussion in this section will be generalized to fuel-rich operating modes for pulverized coal units; however, specific comments concerning the limitations of industrial sized boilers and stoker firing will also be included.

It should be re-emphasized that one of the primary requirements of implementing and operating in a LEA or staged combustion mode is that the boiler be in good operating condition. In this respect, a boiler is not very much different from a car in that you cannot lower emissions if it is in need of a tune-up. Low NOx modes require very carefully controlled air/fuel ratios in different regions of the combustion zone and this is difficult to achieve unless the coal and air handling equipment, burners, and combustion controls are working at their design specifications. Therefore, one of the first steps in implementing a low NOx operating mode, particularly on a retrofit basis, is to inspect the boiler and verify that it meets performance standards in a normal or unmodified operating mode (baseline).

A preliminary boiler inspection and performance check provides many clues concerning off-design operation that could be aggravated by implementing a low NOx mode. In addition to inspecting the burners for burned-off, eroded, or missing parts, the lower furnace region should be examined for flame impingement and ash deposit patterns that indicate unsatisfactory burner operation. Stoker-fired boilers should be inspected for proper adjustments to provide the correct feed rates and distribution patterns, with the grate sections inspected for mechanical integrity and free air flow. Air registers, dampers, and combustion controls should be checked for proper function and control of air to the combustion zone. A reduced excess air baseline performance check including a gaseous emission traverse of the exhaust duct (at the furnace exit) should reveal uniform combustion conditions across the boiler. A minimum excess air test should meet the boiler specifications for the fuel burned and should be consistent with previous performance tests or else the problem must be isolated and rectified. Failure to establish uniform unmodified operating conditions will defeat the purpose of implementing a low NOx mode. For pulverized coal units, coal fineness measurements are recommended for each pulverizer and carbon carryover measurements should be made across the boiler exit at several locations to confirm that there are no problems with individual burners. One should also make every attempt to confirm that all mills and burners are receiving an equal flow of coal through observations of feeder speed, mill power consumption, feeder bar height, etc.

Some of the major problems in the past in implementing satisfactory low excess air or staged combustion operating modes have arisen because of a failure to take the precautions outlined above. With this preparation, the implementation of a low excess air mode is relatively straightforward. The objective is to operate the unit with as low a level of total combustion air to the boiler as possible. The practical limit is reached when one encounters unacceptable levels of smoke, slagging or fouling, combustible losses, carbon carryover, carbon monoxide, or problems of marginal flame stability. In practice, a boiler is never operated at the limit of marginal excess air that borders on one of these problem areas. One must rely on visual observations as well as gaseous instrumentation to establish or confirm satisfactory operating excess air levels with adequate flame stability and no long-term slagging or fouling tendencies.

The successful implementation of a particular low NOx combustion modification will depend upon the flexibility of a boiler system to operate under a configuration for which it may not have been designed. In this respect, stoker-fired boilers may not be as adaptable to low NOx operation as pulverized coal-fired systems. In general, stoker-fired boilers are more limited or restricted in the amount of variation of combustion air flows that can be tolerated under acceptable operations. This restriction is attributable to the stoker's basic construction and the method of coal combustion.

The combustion air is separated into two main streams, the overfire air and the air which enters from beneath the grate. The overfire air is normally adjustable independently of the grate air, and is controlled by adjusting the pressure. The majority of the combustion air is injected from beneath the grate and supports the combustion of the coal bed. On many stoker units, the grate area may be split into only two zones along the travel of the grate. These two zones are normally used to separate the active and burnout zones of the coal bed and air flow is adjustable with register controls. On small units, and especially for spreader stokers, there might be only an open plenum to the entire bed, so that there are no adjustments to bias flows along the grate length. Overfed and underfed stokers have fewer adjustments for fuel distribution (generally only bed thickness) and these boilers may have more adjustments for air flow control along the length of the bed.

Normal operation of a stoker fired boiler requires that problems of clinkering, high grate temperature and incomplete coal burnout should be avoided. These problems are avoided through proper control of the coal distribution, bed thicknesses and combustion air flows. Clinkering, in particular, is a troublesome and potentially hazardous problem which should be avoided. Clinkers are formed when a reduced amount of combustion air is delivered to a portion of the bed of coal and ash. These localized reducing atmospheres result in a low ash fusion temperature, and contribute to the formation of a solid coal/ash mass. This mass prevents air flow through the mass, which further contributes to the formation or growth of the clinker. On spreader stoker units, coal would be continuously fed to the top of the clinker and would build up unburnt fuel. When detected, clinkers are either removed from the grate, or broken up to promote complete combustion.

If the clinkers are allowed to grow in size, and allowed to drop into the ash pit, they can cause fires or explosions, and possibly obstruct the ash pit. Clinker formation is prevented by providing sufficient under grate air, free flowing air passages in the grate, and even bed thicknesses. Grates with local plugs or obstructions in the air passages can promote the formation of clinkers.

Preventing excessive grate temperatures is important to the expected lifetime of the grate. Temperature problems are particularly important for underfed stokers, due to the nature of the combustion process, and their stationary grates. High grate temperatures for all grate types are caused by excessive heat transfer from the furnace walls, and can be traced to fuel distribution problems. The bed of a coal/ash mixture will protect the grate by insulating it from the excessive radiant heat transfer in the furnace. Near the end of the combustion process, only the layer of ash protects the grate surface. A hole in the coal/ash or ash layer or a light spot on the bed may allow excessive heat transfer and grate temperatures, which combined with repeated or continuous exposure, can lead to a reduced grate life.

A secondary problem resulting from a bare spot in the bed is due to a change in the distribution of air. These spots will offer reduced resistance to air flow, and consequently, increase flow in the affected areas. In severe cases this condition may result in starvation in other portions of the bed causing clinker formation.

The most critical component in the prevention of these problems is to provide sufficient and uniform quantities of air to all portions of the bed through the grate. This is seen as the major restriction to the use of low excess air firing in a stoker-fired boiler. If the combustion air is reduced carelessly and beyond certain operating limits which are characteristic of a particular boiler/stoker design, then severe operating problems will result.

Some stoker systems employ windbox systems which allow some flexibility in the air flow adjustments for grate sections parallel to coal travel. These systems allow tailoring of air flows to provide sufficient air in sections having active combustion while reducing flows in grate sections whose beds are predominantly ash. In general, these controls are provided to allow adjustments for changes in the burning characteristics of different coals, as well as changes in coal feed rates. Knowledgeable use of these registers may result in an overall lower excess air operation, and the possibility of reduced NOx emissions, as well as efficient utilization of coal.

These operational problems involved with low excess air firing will also present a limitation to the amount of staging which can be tolerated in a stoker fired system. The concept of staged combustion is to provide a reducing or very nearly stoichiometric combustion at the burner zone (the location of the occurrence of the bulk of the combustion process), while providing sufficient air for complete combustion further downstream. In actual practice, the second stage air is introduced through either burners operating very fuel lean, burners with no fuel flow yet with open air registers or overfire air ports. These same systems can be employed in a stoker fired system with unused oil or gas burners or overfire air ports installed. However, the combustion air provided to the grate must be sufficient to prevent clinkering and other operational problems. While this requirement will almost insure that a sub- or very nearly stoichiometric air flow to the grate section is prohibitive, it does not prevent a NOx reduction by lowering the undergrate air flow from a very fuel lean condition to a level than can be tolerated by the system.

A limited number of tests have been conducted using overfire air ports in a stoker unit. The only stoker-fired staged combustion tests have been performed by using the air register of an unused oil or gas burner to admit combustion air into the furnace as a simulation of an OFA port.

Conservative operating practice to avoid bed clinkering plus less flexibility in combustion air control are two reasons for the generally higher excess O_2 levels found in stoker-fired units. However, this high O_2 operating characteristic is often not reflected in high NO emissions, especially in the cases of the overfed and underfed stokers, whose emissions are much lower than the pulverized coal-fired boilers. To a large degree, stoker-fired boilers are naturally staged by their design. The coal is devolatilized and partially burned in a fuel-rich bed. Above the bed the fuel-rich zones are mixed with the combustion air passing through the grate and combustion is completed.

Satisfactory long term operation usually requires a 0.5 to 1.0% increase in excess O_2 above the minimum to allow for load transients, coal variability and combustion control response in large pulverized coal-fired industrial and utility boilers. In the case of stoker-fed units, much larger excess O_2 factors will generally be required due to less precise control or monitoring of the combustion process, as well as the probability of larger and more rapid load transients than are encountered in the larger boilers.

The implementation of staged combustion by removing burners from service in pulverized coal units introduces several additional operational considerations that were not present in low excess air firing. The two primary parameters are the degree of staging and the burner pattern used to accomplish the desired secondary combustion conditions. Practical limits exist concerning how fuel-rich a burner can be operated and still accomplish complete combustion within the furnace.

In utility boiler applications, it has been found that not all burner patterns have the same effectiveness. A row of air-only burners in the bottom rows of the furnace is least attractive since the air rises immediately into the fuel-rich combustion region defeating the purpose of the staged or delayed combustion. An air-only burner row at the top of the boiler permits the most extensive staging or delayed combustion in that the air tends to form a blanket along the walls with slow mixing. Although this is desirable for preserving fuel-rich operation, it occasionally results in higher than normal overall excess air levels to accomplish complete combustion. A sometimes effective compromise involves placing the next to the top row of burners out of service where the bulk of the burner rows is fuel-rich and the blanket of air sandwiched under the top row of in-service burners provides sufficient air for smoke and carbon burn-out without a significant increase in NO or excessive overall air levels. The optimum burner pattern on a specific unit can only be established by extensive testing.

The successful implementation of staged combustion by means of BOOS requires attention to the following potential concerns:

1. adequate pulverizer or mill capacity with the desired pattern
2. choice of the most effective staging pattern
3. burner logic and flame scanner modifications to implement desired patterns
4. potential coal pipe plugging or fires during pattern installation
5. local reducing environments and long-term fouling or corrosion in BOOS operating mode

While these limitations apply to all types of pulverized coal fired boilers, even more severe limitations involving full load operation are encountered in industrial sized boilers. Industrial sized pulverized coal fired boilers normally utilize only a few burners; therefore, removing one or two burners from service may cut operational burners down by as much as 50%. Even if this were matched by the excess capacity required of the operational mills at the required coal grind fineness, the existing burners might not be sized to handle the extra load. In most cases the capacity of the in-service burners may not be able to handle the full load, due to the large increase in coal demand brought about by fewer mills. Therefore, it is expected and was observed in the coal-fired industrial boiler tests, that losses in maximum load will be encountered in BOOS operation.

Furthermore, due to the small number of burners, an effective staging pattern may not be easily implemented. As an example, to prevent a very serious loss of load capacity, perhaps only one burner out of four can be taken out of service for BOOS operation. In this case, because the burner pattern is normally square, the staging pattern is not as suitable for NOx reductions as a utility boiler whose entire top row of burners can be taken out of service.

It is not uncommon for the coal distribution patterns from mills to the burners to be arranged so that unbalanced boiler flow conditions result when removing any one mill from service. In that case, the individual coal pipes from several mills must be shut off to achieve the desired operation. Potential coal pipe plugging or fires are an associated concern since it is not a desirable practice to simply shut down coal pipes to a burner to establish a pattern without purging the pipes. Otherwise the pipe may plug, preventing operation at a later date and air leakage past the swing valve can lead to fires in the coal pipe if a large residue of coal is left in the line. Therefore, for safety reasons, it is desirable to shut down a mill, purge all the coal pipes, shut down the desired pipes necessary for the pattern, and then return the mill to service. A secondary consideration is the minimum coal flow that has been established for in-service mills for long-term operation which may be a factor if many but not all of the pipes from a given mill are out of service.

The general topic of staged combustion includes biased firing and overfire air implementation and operation. The primary consideration in biased firing is establishing the desired air/fuel ratio gradients in the furnace. One cannot assume equal air distribution to the burners or equal coal flow from a mill to the burner front without confirming this by direct measurement. Therefore, if one establishes a biased firing mode based on this assumption by diverting coal flows to the desired regions, the resultant operating mode may be unsuccessful because the original baseline assumptions were not true. Coal pipes are frequently of unequal length and pressure drop and the coal loadings in pipes have varied by as much as 50% under "normal" operation. In addition, windboxes are not ideal plenums because of obstructions and unbalanced flow patterns, and therefore the air flow to burners varies significantly. Combining these two factors leads to a diversity of local combustion conditions which must be accounted for prior to implementing biased firing.

Potential concerns associated with the implementation of overfire air or NOx port operation are similar to those for BOOS operation with several additional factors. The primary variable is the amount of combustion air diverted through the overfire air ports causing the burners to operate in a more fuel rich mode. However, the same degree of flexibility does not exist as with BOOS in that the port locations cannot be moved and the port area is fixed. Some compensation exists for ports with controllable dampers in that the air flow can be regulated but there is no way of increasing the flow if port area was not properly sized initially. In addition, there is the tendency for air to blanket the furnace walls and not mix effectively if the ports are located above the top row of burners as previously mentioned. An associated disadvantage is the inability to move the port location relative to the fuel-rich burner region if this dimension was not properly optimized at the time of boiler design for proper burnout of smoke and carbon.

5.1.3 Maintenance

The primary maintenance factors in the low excess air or staged combustion operating modes concern the coal, air, burner, and combustion control systems essential to good combustion performance stressed at the beginning of this section.

On the pulverized coal-fired boilers, among the most neglected maintenance items are the burner impellers which frequently are eroded away, cracked, or broken. This can lead to very poor mixing and combustion, carbon carryover, slagging and fouling, precipitator fires, increased excess air levels, etc. Unfortunately, many unit outages occur because of tube failures, feed pump problems, etc. There is also a tendency not to take the time to inspect the burner front. Utilities that have instituted accelerated preventive maintenance schedules on their burners (particularly impeller replacement) have found that many of their related combustion and fouling problems have disappeared. It is likely that undesirable fuel-rich reducing atmospheres and corrosion conditions have been created in boilers more often because of poor burner operation than would occur with staged combustion in combination with an effective accelerated preventive burner maintenance program.

Also of importance for pulverized coal fired systems are mill wear and classifier settings to insure proper uniform fineness for complete combustion. Pulverizers should be properly serviced to maintain the desired grinding characteristics. Coal feeder operation should also be monitored and maintained to insure uniform coal distribution to the burners. One of the classic offenders in this regard is the feeder bar height setting which should be periodically checked whenever a mill is down. Mill power consumption relative to feeder speed is usually an indication of improper feeder setting or feeder obstruction. This can upset NOx emissions in the same manner as biased firing if not properly observed.

On stoker fired boilers, the systems which feed the coal on to the grates is of most importance to good combustion performance. Under and over-fed stokers are relatively simple systems which only require adjustment of a "sluice" gate or coal ram system to feed the coal onto the bed. These systems normally present no problems when in working order.

Spreader stokers are a bit more elaborate in design and operation, therefore they can pose additional problems of coal feed distribution. As shown in Fig. 3-12, the spreader stoker feeds the coal from the hopper by the action of a reciprocating feed plate. The coal flows over the spill plate, contacts the spinning rotor drum, and is thrown into the furnace. Spreader stokers utilizing a traveling grate usually throw the bulk of the coal into the rearward two thirds of the grate, where most of the combustion process occurs. On these systems, the grate moves towards the stoker, therefore the last one-third of the bed allows for complete burnout.

The position of the spill plate determines the location where the coal will drop on top of the spinning rotor. This positional adjustment will in turn allow the coal to be thrown at different angles relative to the bed. Therefore, proper adjustment of the spill plate will partly determine the proper distribution pattern of coal into the bed. Occasionally, due to heating from the furnace, coal may become coked on the end of the spill plate which changes its effective length or position and changes the feed pattern. The blades attached to the rotor drum are also important in providing the correct coal distribution on to the bed surface. The blades are designed to provide the desired coal throwing pattern for the size ranges of coal used in the stoker. Should a blade become excessively worn or damaged, the optimum coal patterns may not be attainable, which in turn may produce undesirable combustion characteristics.

5.1.4 *Corrosion*

An additional operational problem which has drawn considerable controversy and concern in the utility boiler sector is the possibility of increased corrosion of the interior metal surface in a boiler during low NOx operation. The combustion modification methods showing the most promise of reducing NOx formation in coal-fired boilers involve the reduction of the amount of air present in those regions of active combustion. The concern in employing two-stage combustion in current or future boiler designs is the expectation of an accelerated corrosion problem which stems from the creation of a reducing atmosphere in the furnace.

Current low NOx methods of staged combustion may not employ a reducing atmosphere; however, they do approach a less fuel lean operating condition in the primary zone. This condition in the primary stage would increase the possibility of creating a localized reducing atmosphere and therefore, a greater possibility of increased corrosion. Since the practical application of staged combustion on coal-fired boilers is in an early stage, determination of the severity of a corrosion problem has not been resolved.

The following section will deal with the history and mechanisms of corrosion involved with coal-fired boilers, followed by a brief review of current corrosion studies and the corrosion in industrial boilers.

5.1.4.1 *Corrosion in Pulverized Coal-Fired Boiler Furnaces*

Occurrence and Location in Wall Tubes - Radiant Section

High temperature fire side corrosion of water walls in the radiant section of pulverized coal-fired boilers is generally confined to areas of flame impingement and/or slag buildup. The slag deposit is usually coupled to a reducing atmosphere caused by flame impingement since the fusion temperature of coal ash is lower by several hundred degrees F under reducing conditions than for oxidizing atmospheres. This reducing atmosphere allows a stickier, more plastic ash to be deposited on the relatively cold wall tube. This slag deposit then becomes the medium by which the corrosion of the tube metal takes place.

Reid, et al. (Ref. 5-2) in an extensive field investigation of external corrosion in boilers, found that serious metal loss from wall tubes took place only under layers of slag, that the pattern of corrosion was related to flame configuration along the walls of the furnace, that the rate of heat transfer was insignificantly higher in corroded areas than in the rest of the wall, and that tube metal temperatures were approximately the same whether or not corrosion occurred.

In Russia, high temperature corrosion of water walls in boilers burning pulverized anthracite in a slag tap mode has been experienced. Ivanova and Marshok (Ref. 5-3) investigated this problem and concluded that corrosion of the lower radiant section water walls develops at those points where the flame is in contact with the water walls for a long time and where the atmosphere is of a reducing nature. The rate of corrosion becomes appreciable at temperatures of the tube walls of 540 °F and increases with increasing temperatures. At lower tube temperatures corrosion does not develop.

Another Russian study by Pekker and Lipov (Ref. 5-4) came to the same conclusion that the concentration of the most intense damage occurred only in the zone of active sweeping of the water wall by the flame. However, they attribute the tube metal loss to a combination of erosion and corrosion.

In boilers where the entire burner region is run fuel-rich for NOx control, it is possible to have recirculation zones outside the primary burner regions where fuel-rich combustion products and ash might scrub the tube wall and lead to ash deposits and corrosion. This could be the case, for example, in areas under the bottom row of burners or in the corners of the furnace. Such regions will be identified by increased slagging.

5.1.4.2 *Mechanisms of Fireside Corrosion in Pulverized Coal-Fired Boilers*

Two types of corrosive attack have been identified in boilers firing coal with appreciable sulfur content. Reid (Ref. 5-2) discusses the relative occurrence of both the alkali iron trisulfate and the iron sulfide modes of attack. The results of his work indicate that the sulfate type attack predominates over the sulfide type. Sulfide deposits were found in some areas of the boiler, but large amounts of carbon, up to 5%, were also noted in these same areas, indicating that the normal oxidation process had not taken place.

Typical chemical analysis of the deposits found in corroded areas of tubes whose metal temperatures never exceed 800 °F show the following typical characteristics (Reid, Ref. 5-2):

- high alkali content
- high SO_3 content
- high water solubility

The ratio of the water solubility to SO_3 content was nearly constant at an average value of 1.78. These data were interpreted as indicating the presence of a single chemical compound. The low pH values characteristic of these deposits indicates their acidic nature.

The water soluble deposits were pale, bluish white, and had a glossy appearance (Ref. 5-2). These deposits came to be known as "enamel" because their tight adherence to the wall tubes and their glasslike nature gave them much the same appearance as enameled cooking ware. One peculiarity of this deposit was that it became attached to tubes that had never been hotter than 800 °F, although its melting point was 1000 °F.

In oxygen-deficient atmospheres, the sulfur from the decomposition of pyrites, FeS_2, will not all be oxidized to sulfur dioxide. Halstead, et al. (Ref. 5-5) showed that the sulfur released by the dissociation of FeS_2 to FeS and S atoms was formed in 0.5 sec. at a temperature of 2000 °F under conditions that would exist in a pulverized coal-fired furnace. His experiments demonstrated that within the short residence time in the flame, the sulfur and metal sulfides could be deposited on furnace-wall tubes. The presence of FeS in the deposits formed on badly corroded boiler tubes has been reported by Reid (Ref. 5-2) in this country and by Pekker (Ref. 5-4) and Ivanova (Ref. 5-3) in the Soviet Union. These sulfide deposits are almost always accompanied by carbon. The Windsor station of Table 4-13 is an example of this kind of attack. The high concentrations of iron, sulfur and carbon contrast with the results of the other analyses.

Cory, et al. (Ref. 5-6) showed in laboratory experiments that iron is corroded rapidly in the presence of FeS_2 at temperatures in the range 700-1000 °F. Under these conditions, corrosion by FeS_2 was responsible for the attack. Poor pulverization and poor mixing of coal and air from the burner resulting in unburned coal being deposited on the walls can lead to conditions of pyrite attack on the furnace tubes. The FeS_2 carried with this coal oxidizes slowly, evolving sulfur, which then could react with the tube metal to give the FeS deposits. Some of this FeS could subsequently be oxidized to Fe_3O_4; both have been identified in the deposits by X-ray diffraction analysis.

Additional evidence for this mechanism was obtained when corrective measures were applied in two of the furnaces that had severe corrosion in areas with FeS deposits. Both the rapid corrosion and the FeS were eliminated when pulverizer adjustments were made and coal distribution pipes were repaired, thus insuring that the carbon and sulfur would be completely oxidized before reaching the walls.

Data are not available on the extent or duration of reducing conditions required to convert the alkali iron trisulfates into sulfides. The ratio of H_2 to H_2O and of CO to CO_2 must be fairly high for the conversion to occur. More importantly, the trisulfates will not form except in the presence of SO_3; some 250 ppm is necessary at 1000 °F to produce these compounds. Since SO_3 is not formed when the oxygen level in the flue gas is less than 0.2 percent, it is probable that gas phase SO_3 does not contribute to trisulfate formation. However, the oxygen-deficient conditions may lead to deposition of sulfur or iron pyrites, with subsequent reaction leading to corrosion of the boiler tubes.

Sulfide corrosion is particularly serious when the tube metal contains nickel since the corrosion propagates along the grain boundaries. The resulting nickel sulfides are low melting compounds, and being liquids of more than one valence state they can transport sulfur from the edge of the grain boundary deep into the metal. Chromium sulfides do not melt as readily and therefore do not migrate as easily. Chromium alloys are therefore more resistant to corrosion.

Ivanova, et al. (Ref. 5-3) studied the problem of corrosion of the lower radiant section in slag tap pulverized coal fired boilers firing anthracite. They also found considerable amounts of Fe_2O_3 and FeS in the corrosion deposits leading them to assume a sulfide type corrosion mechanism. They felt that the poor reactivity of the anthracite fuel was responsible for localized highly reducing conditions within the furnace. They concluded that:

- air control to the burner was critical and needed to be more closely controlled as the load changed
- fuel/air ratios must be uniformly distributed over all burners
- flame impingement on the water walls must be prevented

These results are in agreement with the results of previous workers and as such lend support to the iron sulfide mechanism.

Carbon monoxide itself has no direct effect on boiler steels which could cause corrosion. However, there can be an indirect effect if the CO reduces the thickness of the protective oxide scale thereby exposing fresh tube metal to oxidative attack when conditions change from reducing to oxidizing.

Excessive loss of tube metal in large steam generating incinerators in Europe has been attributed to this action. The European solution to the problem has been to shield the steam tubes with silicon carbide. No definite proof exists that tube wastage is always accelerated by such alternating conditions. However it is worthy of consideration since two stage combustion could very likely lead to an area intermediate between the two combustion zones where the atmosphere may shift rapidly and unpredictably between reducing and oxidizing conditions.

5.1.4.3 Corrosion in Stoker-Fired Boilers

Stoker fired boilers are susceptible to corrosion mechanisms on the grate surfaces and to the lower portions of water tubes near the coal beds. Due to the method of coal combustion on a bed, the contact between coal ash and metal parts of the stoker always happens. This represents an ever present opportunity for corrosion. Coal ash below a temperature of 1800 °F is said to be solid and chemically inert and between 1800 and 2200 °F, the ash/slag and metal reactions are unlikely, except when reactive fluxes such as limestone are present.

Corrosion of metal parts is possible by a mechanism involving a reaction of iron and FeS (Ref. 5-2). Inorganic iron sulfides account for roughly half of the sulfur content of coals, and are dissociated to form FeS at temperatures between 500 and 1000 °F. They can lead to corrosion of iron at lower temperatures. Iron and FeS can react to form a eutectic with a melting temperature of 1805 °F, while FeO and FeS can form a eutectic with a melting temperature of only 1724 °F. These temperatures are in a range of those attainable on the grates when plugs prevent free air flows, or during sheet clinker formation. Additionally, the FeS produced is not likely to form Fe_2O_3 when there is a block air flow, and can react with iron. In the same manner, the side water walls which are in close contact with the fuel bed can corrode.

Therefore, plugging of the grate air passage may not only lead to overheating the grate, but also can promote corrosion, which attacks the grate and therefore lowers expected lifetimes. The possibility of corrosion further complicates the problems of attempting to reduce the amount of under grate air flow as a NOx control technique. According to Reid (Ref. 5-2), corrosion of grates was an "annoying" problem which has been alleviated only due to decreased stoker populations. However, in the industrial coal-fired boiler category, the stoker remains as a major method of combustion and cannot be easily dismissed. In some applications, the addition of silica compounds (sand) has been used to change the fusion temperature of the ash and keep the fluid point high.

5.1.4.4 Recent Studies of Corrosion

With the practical implementation of staged combustion on coal fired utility boilers and with the concern with corrosion, experimental corrosion studies have been initiated within the last few years. In the early tests, sponsored by the EPA, corrosion probes were used as a measurement of the rate of corrosion. The probes were constructed of an assembly of preweighed metal coupons which were internally cooled to the desired temperature. The assembled probes were then inserted into the furnace through ports in the walls and allowed to remain for ∿300 hours.

The results of these short term tests have been controversial due to their rapid rate of metal loss (much higher than actual wall losses), wide variation in sample losses, and a possibility of damage to the sample coupons during probe disassembly. Furthermore, a question of the role of internal coupon oxidation by the cooling air has been raised (Ref. 5-7). In laboratory experiments, coupons which were subjected to similar temperatures and fresh air oxidation showed losses similar to those for coupons subjected to boiler tests. In addition to these possible problems, the test length using corrosion probes is normally 300 to 1000 hours which may not be a long enough test to be representative of boiler conditions.

A list of the difficulties and uncertainties of corrosion probe testing includes the following observations:

- the results are very dependent upon method of sample preparation, processing, and measurement
- the increased coupon temperature used until recently is not representative of actual boiler tube operating conditions

- the exposure in the test boiler may not be the same as for the tube wall and is very location dependent
- the operating temperature of the coupons frequently is not uniform and carefully controlled
- test coupons are occasionally damaged in the disassembly of probes
- the rate of oxidation or corrosion is not always linear with time and the initial weight loss may be higher than in subsequent periods biasing the results of short-term tests to higher than normal corrosion rates
- a significant portion of the corrosion occurs on the internal surfaces of the coupons, probably due to oxidation of the hot metal by the cooling air
- there is speculation that in some cases the measured corrosion may be no greater than fresh air oxidation at the elevated temperature.

The latest EPA sponsored corrosion tests are attempting to resolve many of these problems with long term corrosion panels installed in a boiler. These panels are measured before installation and are then welded into place to become an integral part of the water wall. The length of the tests under low NOx operation is expected to be $\sim$1 year. In addition ultrasonic measurements of the waterwall are being used as well as corrosion probe experiments of varying exposure times.

Since the corrosion results from the most recent tube panel tests are not yet available and past tests have a great deal of uncertainty in these results, no specific conclusions can be made at this time about possible increased corrosion with staged combustion on pulverized coal-fired boilers. When the corrosion testing on utility boilers has progressed sufficiently to produce an adequate answer that finally resolves the corrosion question, the results can probably be applied to large pulverized coal industrial boilers. However, no recent work has been conducted on the corrosion problem with stoker fired units. Interest in this type of work will probably evolve only when forms of staged combustion in stokers become of practical interest.

5.1.5 Slagging and Fouling Concerns in Low NOx Modes

Although corrosion is one of the primary concerns in low NOx operating modes, an associated concern is slagging and fouling of tube surfaces which can lead to lost capacity and operational problems of slag removal and efficiency penalties due to reduced heat transfer. In stoker-fired units, slagging is generally not as great a problem due to lower furnace temperatures and the different mode of combustion.

Many of the same factors that result in furnace corrosion are also the cause of excess slagging. Thus one must be cognizant of any furnace slagging conditions which might arise in the course of setting up low NOx operating conditions.

Slag deposits are formed when molten or fused ash particles entrained in the flue gas stream strike a wall or a tube surface. They become chilled and solidify. The strength of their attachment is influenced by the temperature, by the physical shape of the surface, by the direction of the gas stream, by the force of impact, and by the melting characteristics of the slag. Coal with low ash fusion temperature (AFT) (i.e., coal ashes which are plastic or semi-molten at temperatures below 2200 °F) have a high slagging potential. Fusion temperature is generally defined by a series of laboratory tests in which a cone of ash is heated to different temperatures and the shape of this cone observed. These tests are conducted in either reducing or oxidizing atmospheres. Generally, fusion temperatures measured in a reducing atmosphere are lower than those measured for the same ash in an oxidizing atmosphere. In particular, as the amount of iron in a particular coal ash is increased, the difference between fusion temperatures measured in reducing and oxidizing atmospheres increases.

The basic approaches to the reduction of slag deposition and retention are three-fold. First, avoid reducing atmospheres in the region adjacent to tube walls. Although this may require considerable effort to achieve in low NOx operating modes, it is important since if there is any benefit to be gained in terms of a higher ash fusion temperature under oxidizing conditions, this will help insure the higher temperature.

Reducing modes can occur:

- as the result of poorly implemented low NOx operation
- at each burner because of its peculiar combustion profile (Burner related reducing modes will result in a reducing type slag distributed throughout the gas.)
- between burners due to poor flame shape and inadequate interburner spacing
- from gross fuel air maldistributions caused by closed registers, poor windbox design and a general imbalance of fuel and air to burners

Reducing local furnace gas temperatures near the wall below the solidification temperature of the ash is another approach to reduce slagging.

The third technique is to move the slag deposit and/or change its properties so existing removal equipment can efficiently dispose of it. This can be an effective technique when combined with the elimination of reducing atmospheres by burner adjustments.

Combining lower peak flame temperatures with the control of air to preclude the existence of reducing zones near furnace walls can be an effective slag reduction technique as well as lowering the NOx emission levels.

The preceding paragraphs have outlined some of the approaches being considered in slagging and fouling control. Conventional approaches of mechanical slag removal are the subject of design studies concerned with blower placement, removal medium (air, steam, water, etc.), and blowing pattern. Additional factors include boiler tube spacing, convective section design, etc. Obviously, additional research is needed in new concepts for furnace slagging and control for the interim period before beneficiated coal use becomes widespread.

5.2 *ENERGY CONSIDERATIONS ASSOCIATED WITH THE IMPLEMENTATION OF LEA AND STAGED-COMBUSTION OPERATING MODES*

An important consideration in the use of combustion modifications to reduce NOx emissions is the associated influence on unit operating efficiency. An improvement in efficiency could result in fuel cost savings that offset the costs of the combustion modification thus making the implementation attractive from both the energy and air pollution standpoints. A net decrease in efficiency, however, could impose an additional cost burden and seriously impede its application on industrial sized units.

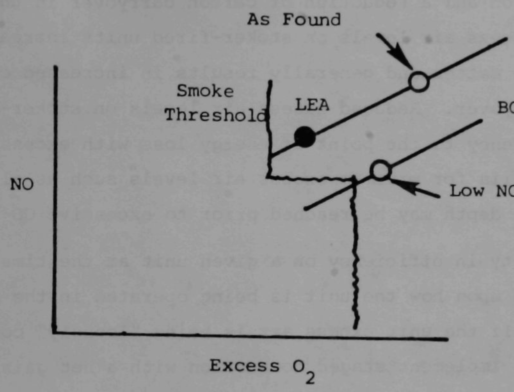
5.2.1 *Factors Affecting Efficiency*

Boiler efficiency is the measure of the efficiency with which the heat input to the boiler (principally the heating value of the fuel) is converted to useful heat output in the form of steam. Improvements in efficiency result primarily from reductions in the waste heat energy losses in the stack gases that accompany reductions in excess air levels. Lower excess air levels reduce both the mass flow and temperature of the stack gases.

For each firing mode, a "minimum excess air level" can be determined below which significant increases in combustible emissions (CO, particulates and smoke) occur indicating incomplete combustion of fuel and a corresponding efficiency decrease. The minimum excess air level or "minimum O_2" is the point of peak operating efficiency. The minimum O_2, determined by the trade-off between lower waste heat losses and increased combustible losses, is one of the primary controlling parameters in optimizing boiler efficiency.

Since staged combustion operating modes result in more fuel rich combustion, there is a tendency to operate at unnecessarily high excess air levels. In most cases, an increase in minimum excess air levels relative to baseline operation should not occur if the final operating excess air level is properly chosen.

The sketch below of NO emissions and smoke threshold dependence on operating excess oxygen level illustrates the typical situation in implementing LEA and staged combustion on a pulverized coal-fired unit. The operating excess air level during "as found" operations with all burners in service frequently



is much higher than necessary for efficient operation to provide the control system and operator with a wide margin above the smoke threshold for operating convenience. LEA operation is achieved by reducing air flow along the NO versus excess air curve from the "as found" condition to the point of the onset of smoke. A practical operating minimal excess air is generally set at 0.5 to 1.0% O_2 above this minimum to allow for variations in fuel and air conditions or unit disruptions.

If one were to implement staged combustion (shown as the lower curve) at the same excess oxygen level as LEA, one would increase combustible emissions for the fuel-rich operating modes that accompany staging. Unsafe boiler conditions may occur in some cases. However, a 0.5 to 1.0% increase in operating excess oxygen level will result in operations on the acceptable side of the smoke threshold by the same margin as in the LEA mode. Although one has "given up" some excess O_2 to implement staged combustion, the final operating O_2 level occasionally is better than (or frequently at least equal to) the "as found" level prior to its implementation.

For stoker-fired units, a somewhat different situation exists. As mentioned previously, the bulk of the combustion air is supplied through the grate. Unlike pulverized fired units where increased excess air generally promotes complete combustion and a reduction of carbon carryover in the particulates, increased excess air levels on stoker-fired units increases the entrainment of particulate matter and generally results in increased combustible losses through carbon carryover. Reduced excess air levels on stoker-fired units will increase efficiency to the point of energy loss with excessive CO emissions. Other criteria for minimum excess air levels such as clinker formation or excessive bed depth may be reached prior to excessive CO levels.

A net gain or penalty in efficiency on a given unit at the time of implementation will depend upon how the unit is being operated in the baseline or "as found" mode. If the unit excess air is being "loosely" controlled, it is possible to implement staged combustion with a net gain in efficiency. However, if the unit initially is being operated close to the smoke and carbon carryover threshold, it is likely that a higher excess air level will be required with staged firing resulting in an efficiency penalty.

5.2.2 Efficiency Test Results

Boiler efficiency measurements in normal, low O_2, and staged operating modes were made in accordance with the ASME Power Test Code during the several field test programs discussed in Section 4.0. Tables 5-1 and 5-2 list boiler efficiencies calculated for each boiler tested along with other pertinent boiler performance information. Differences in calculated boiler efficiencies between baseline, low O_2, and staged test conditions provide a comparison of any efficiency debit or credit accruing to modified operating conditions. Unfortunately, only limited data on the carbonaceous content of the particulate emissions were available for many of these tests. In those cases, the

Table 5-1. Summary of Boiler-Performance Calculations, Stoker-Fired Units

Boiler I.D.	Stoker Type	Firing Mode	Test No.	Load (10^3 lb/hr)	% O_2	NO @ 3% O_2	% Carbon In Particulate	Boiler Efficiency	Referenc
U. Wisconsin-Madison 2	SS	Baseline	14	90	9.1	436	46	76	1
		Low O_2	15	90	7.3	379	50	78	
Fairmont 3	SS	Baseline	3	49	9.3	320	26	78	1
		Low O_2	5	49	8.2	265	39	80	
Willmar 3	SS	Baseline	23	115	8.2	491	27	81	
		Low O_2	33	110	6.6	375	28	82	
IB-13	SS	Baseline	134-2	82	6.2	314	--	87	2
		Low O_2	135-2	82	4.7	221	--	88	
		Staged	136-3	82	6.1	229	--	87	
IB-15	TGrt.	Baseline	165-1	104	9.5	163	--	76	2
		Low O_2	166-4	105	8.7	124	--	78	
		Staged	168-3	102	9.0	163	--	76	
IB-8	UFS	Baseline	16-12	47.5	6.6	260	--	76	
		Low O_2	16-10	45	4.9	192	--	77	
IB-1	SS	Baseline	18-3	106	7.0	366	--	82	
		Low O_2	18-6	114	4.9	326	--	82	
IB-11	SS	Baseline	19-6	40	8.0	457	--	81	
		Low O_2	19-9	41	5.8	324	--	82	
IB-9	UFS	Baseline	17-6	46	9.8	218	--	72	
		Low O_2	17-15	46	7.0	196	--	75	
IB-6	SS	Baseline	27-1	120	10.3	550	--	81	
		Low O_2	27-4	123	8.9	445	--	82	
IB-7	SS	Baseline	28-2	162	10.8	502	--	80	
		Low O_2	28-6	150	8.9	341	--	83	
		Low NOx	28-15	145	12.6	350	--	80	
Boiler A	SS	Basin	35	225	6.0	394	--	78	
		Low O_2	36	240	4.7	344	--	80	
		Staged	34	225	5.9	353	--	81	
U. Wisconsin Stout 2	VGS	Baseline	14	25	9.3		46	76	
		Low O_2	12	26	5.2		17	80	

Table 5-2. Summary of Boiler-Performance Calculations, Pulverized-Coal Units

Boiler I.D.	Firing Mode	Test No.	Load (10^3 lb/hr)	Percent O_2	NO @ 3% O_2	% Carbon In Particulate	Boiler Eff.
IB-2	Baseline	26-1	181	5.3	364	--	86
	Low O_2	26-2	183	4.5	346	--	86
IB-3	Baseline	78-1	260	5.8	473	--	86
	Low O_2	78-7	261	4.8	487	--	86
IB-14	Baseline	131-4	130	7.4	915	--	88
	Low O_2	132-1	132	6.6	850	--	88
	Baseline[a]	133-1	66	7.2	615	--	88
	Staged	133-2	63	7.5	591	--	88
IB-5	Baseline	156-2	400	8.6	337	--	76
	Low O_2	158-1	390	8.1	330	--	79
Fremont 6	Baseline	11	115	3.8	390	0	88
	Low O_2	16	113	3.4	341	1	88

[a] Low load

efficiency was calculated based on an assumed particulate/carbon content. The corresponding efficiency changes between baseline and modified combustion conditions therefore represent the reduction in waste heat stack gas loss only.

Results of tests conducted on twelve stoker-fired units are presented in Table 5-1. It can be seen that operating efficiency increased for nearly all cases with the implementation of LEA operation. Efficiency improved an average of one percent with decreases in excess O_2 of one to three percent. Operation with a staged configuration resulted in efficiency levels comparable to the "as found" (or baseline) levels. In all but one of the test cases, the excess O_2 level used during staged firing was lower than that under baseline conditions. As shown in Table 5-1, the change in the carbonaceous content of the particulates was variable among the available test results. No definite conclusions as to the influence on operating efficiency can be made based on these test results.

Results of tests conducted on five pulverized coal-fired industrial sized units are presented in Table 5-2. The efficiency generally remained unchanged using either LEA operation or staged combustion. The one exception to this was the three percent increase in efficiency with LEA operation on Boiler IB-5.

Data on the influence of staged combustion (BOOS) were available on one unit operating at approximately 30% load. Efficiency again remained unchanged between the baseline and staged combustion test conditions.

In general, staging the combustion process and reducing excess air levels for a boiler to reduce NOx emissions tend to increase the amount of unburned combustibles somewhat. However, the debit in efficiency resulting from such incomplete utilization of the fuel is offset by the improved efficiency resulting from lower excess air operation. Therefore, the conclusion reached based on these results is that "low NOx" firing has no major effect on boiler efficiency.

5.3 POTENTIAL SECONDARY ENVIRONMENTAL IMPACTS ON AUXILIARY EQUIPMENT OF LOW-NOx OPERATING MODES ON INDUSTRIAL COAL-FIRED UNITS.

The use of combustion modification to reduce NOx emission could possibly increase the emission of secondary pollutants and/or adversely affect auxiliary equipment, such as a particulate collection device. Proper implementation of NOx reduction techniques requires careful monitoring of secondary pollutants, since their excessive emissions can also represent some operational constraints on the boiler.

With the exception of CO, data for secondary pollutants are often scattered or sparse. CO data are normally taken with the NO and O_2 readings since excessive CO emissions give a good indication of improper levels or distribution of combustion air. Many times, the CO levels will be near zero for all test cases. The same holds true for hydrocarbons, although not recorded as often as CO emissions; frequently the hydrocarbon emissions remain at levels of <30 ppm for most test cases.

While the hydrocarbon and CO emissions are measured by gaseous sampling techniques, particulate sampling involves the removal of a representative solid sample from the flue gas stream. Because particulate sampling is more difficult to do and more time consuming for a single test point, particulate loadings are not as well documented as other pollutant emissions. While particulate data may be reported, repeated samples are often difficult to find, and therefore the particulate measurement may be taken for a baseline operation, and not for a low NOx mode. In some cases, particulate measurements during a low NOx mode (such as low excess air) may be run, but without the corresponding NO measurements. In still other cases, no comparable baseline particulate tests could be found that could be compared to a low NOx particulate test.

In effect, while secondary pollutant data may have been recorded during the course of a NOx test program, they are often inadequate for the determination of secondary pollutants' sensitivity to operational changes.

A related topic is the effect of low NOx combustion modes upon auxiliary equipment. The equipment which would be most affected by combustion modifications consists of devices downstream of the boiler, such as a cyclone dust collector or electrostatic precipitator. Of prime concern are the possibilities of increased particulate loadings, increased carbon content of fly ash, and decreased collection efficiencies of these devices. Either an increase in uncontrolled emissions or decrease in collection efficiency can lead to an increase in stack particulate emissions, while increased carbon content may result in decreased efficiency or in the extreme case, possible fires in the collection device.

5.3.1 Pulverized-Coal-Fired Boilers

Table 5-3 presents the secondary pollutant emissions data for selected NOx reduction test runs for three face fired boilers. These tests are grouped according to comparable tests due to changes in load or other operating conditions. It should be mentioned that in some test sequences, different coals were used in the same boiler, therefore, some tests might not be comparable (even though O_2 or load are equivalent).

The first group of tests was performed on IB-14, and includes data for low excess air and burners out of service tests. The first two tests are for low excess air operation and show a moderate reduction of NO (915 ppm to 850 ppm) with a 0.8% change in O_2 level. CO emissions were effectively zero for all operating configurations. Similar results were obtained in the BOOS test, but at a lower load. Significant reductions in NO by employing two BOOS are observed, yet CO emissions did not increase. Only one particulate test of the baseline uncontrolled loading was taken.

Three sets of data are presented for Alma 3, a face-fired boiler utilizing an electrostatic precipitator. The first set shows the impact of BOOS operation on CO and hycrocarbon emissions. While large reductions of NO are recorded, the implementation of the two tests utilizing three burners and the three burner/one BOOS tests are shown to increase CO emissions significantly. The CO emission increased from 7 ppm at baseline to approximately 1500 ppm on the two tests. This probably resulted from the decrease in excess O_2 levels which dropped approximately 1.0% from a baseline of 2.9%. Had the O_2 levels been increased to near baseline levels, effective CO burnout may have been achieved with significant NO reductions. The NOx emission reductions cannot be determined from the data shown. Interestingly, the hydrocarbon emission data did not increase with the CO, and remain relatively constant for all conditions.

The second set of data for Alma 3 presents particulate emissions data for low excess air operation. Unfortunately, no corresponding gaseous emission data were given for this test. The baseline O_2 level of 3.9% O_2 was reduced to a 1.7% O_2 for LEA. While the uncontrolled emission of particulates was not recorded, the controlled emission from the electrostatic precipitator dropped from 0.027 to 0.018 lb/10^6 Btu. The second LEA test shows the effect of reducing the O_2 level too far (only 0.1% lower than the previous case) resulting in a large CO emission. While the uncontrolled particulate emission increased from 5.13 to 6.74 lb/10^6 Btu, the controlled emission remained constant. In this case, the overall collection efficiency of the electrostatic precipitator increased. This series of tests therefore showed no detrimental effect on particulate emission control from LEA firing.

The third set of data for Alma 3 presented in Table 5-3 gives the results of LEA operation on particulate emissions at reduced loads. In this case, both the controlled and uncontrolled emission levels remained essentially the same even though the excess O_2 level was reduced by 2.6%. Evidently, the baseline O_2 level of 12.8% was far in excess of that required for complete combustion.

The third pulverized coal fired boiler is Fremont 6, a face fired unit with a mechanical particulate collection device (cyclones). The three test points show the effect of excess O_2 on NO, CO, particulates and hydrocarbon emissions. The NO behaves as expected, decreasing with reduced excess O_2. CO follows the O_2 level, increasing with decreasing O_2, although

Table 5-3. Secondary Pollutants, Pulverized-Coal-Fired Boilers

Unit	Test No.	Load 10^3 lb/hr Steam	O_2 %	NO ppm at 3% O_2	HC ppm at 3% O_2	CO ppm at 3% O_2	Boiler Efficiency Percent	Part. Loading ($lb/10^6$ Btu) Unc / Con	Collect Efficiency %	Combustible In Ash %	Test Type
IB-14	131-4	130	7.4	915	--	0	88	5.31/--	--	--	Base
SW	132-1	132	6.6	850	--	0	88	--	--	--	Low O_2
	133-1	66	7.2	1006	--	0	88	--	--	--	Low Load (Four Burners)
	133-2	63	7.5	591	--	0	88	--	--	--	Two BOOS
Alma 3	40	196	1.9	361	25	1536	--	--	--	--	Three Burners
SW	41	196	2.2	277	23	1476	--	--	--	--	One BOOS, Three Burners
ESP	42	200	2.9	579	28	7	--	--	--	--	Base (Four Burners)
	4	200	3.9	--	--	--	--	5.13/0.027	99.47	--	Base
	3LT	200	1.7	--	--	0	--	--/0.018	--	--	Low O_2
	4LT	200	1.6	--	--	4000	--	6.74/0.026	99.61	--	Low O_2
	18	60	12.8	--	--	--	--	8.53/0.044	99.49	10.7	Low Load
	21	60	10.2	596	--	36	--	8.62/0.032	99.60	4.4	Low O_2
Fremont 6	13	112	5.1	438	46	10	87.8	2.78/0.67	76.0	0.5	High O_2
SW	11	115	4.3	390	33	12	88.3	2.74/--	--	0.3	Base
MC	16	113	3.4	341	63	61	88.3	2.32/0.62	73.3	0.9	Low O_2
	3	108	5.4	591	--	11	87.5	2.64/1.02	61.4	1.1	Base
	7	108	3.6	--	62	17	88.6	2.12/1.00	52.7	0.7	Low O_2

SW - Single Wall Fired

ESP - Electrostatic Precipitator

MC - Mechanical Collector (Cyclone)

UNC - Uncontrolled

CON - Controlled

most of the increase is shown at the lowest O_2 level. The hydrocarbon emissions fluctuate slightly with excess O_2, remaining at essentially baseline levels. Uncontrolled particulate emissions decrease with decreasing O_2, though again most of the reduction takes place at the lowest O_2 level. Controlled emissions in the case of the high and low air test are also reduced in a similar manner; however, the collection efficiency drops from 76 to 73.3 percent. This may be a consequence of the reduced O_2 levels which correspond to a bulk flow rate change of approximately 9%. This lower bulk flow may impair cyclone operation to a certain degree; however, overall stack particulate emissions are improved. A similar change is noted for tests three and seven, although the collection efficiencies are much lower than in the previous case. This may be due to a coal switch between test runs.

Combustibles in the fly ash are shown for the last series of Alma 3 and for the two at Fremont 6. It would be generally expected that combustibles in fly ash would behave similarly to CO or hydrocarbon emissions, since they all give an indication of incomplete combustion. The results from these three tests are mixed, and in only one case did the combustible content increase with low O_2 firing. Comparing tests 11 and 16 at Fremont 6, a 0.6% increase in fly ash combustibles was recorded for the decrease in O_2 level of 0.9%. Corresponding to this increase was an increase in CO and hydrocarbon emissions. In the other two cases, the combustibles content was reduced.

Based upon the limited tests presented here, there appears to be no definitive impact on secondary pollutants such as CO, hydrocarbons, and particulates, from properly implemented low excess air or burners out of service. Excessive emissions can result (especially in the case of CO) when these combustion modifications are used too zealously. Mixed results were obtained from the uncontrolled emission of particulates. With low excess air implementation, however, the controlled emission of particulates remained essentially constant. Collection efficiency varied according to the control device. The limited data suggest that electrostatic precipitators may increase collection efficiency, and cyclone collector efficiencies are reduced. Combustible content of the fly ash was unaffected under low NOx modes. As a whole, there appeared to be no detrimental effects from the proper implementation of LEA or BOOS in pulverized coal industrial boilers and in some cases, increases in efficiencies are noted.

5.3.2 Stoker-Fired Boilers

Table 5-4 presents secondary pollutant emissions data for selected NOx test runs from both spreader and overfed stokers. The data have been subdivided within the various boiler units to denote changes in load, coal type, etc.

Secondary pollutant data for IB-6 and IB-7, both spreader stokers, are very limited. As shown in Table 5-4, no CO emissions were measured under baseline or modified combustion conditions. The only particulate data of significance came from a baseline versus staged combustion test on IB-7 where uncontrolled particulate loading was reduced from .476 to .345 lb/10^6 Btu with implementation of the BOOS operation. Moderate differences in load (15 k lb/hr) and O_2 (.7%) between the two runs may have had some effect on these levels.

The data for IB-11 and IB-12 include baseline and LEA tests only. Controlled particulate loading increased with low excess O_2 from IB-11, but remained constant with low excess O_2 from IB-12. A beneficial reduction in CO emissions was gained from both boilers.

The data for IB-13 have been divided into two groups: (1) normal load under baseline and LEA conditions along with air adjustments to overfire nozzles, and (2) low load with various O_2. The first set of data has particulate information only for the baseline and LEA cases. The drop in controlled particulate loading for LEA is similar to that observed for IB-11. CO emissions were affected adversely by air adjustments. For the low load cases, CO emissions were essentially unaffected by alterations in O_2.

The data for Willmar 3 have also been divided into two groups: (1) western coal, and (2) eastern coal. For the first group of data, controlled particulate loading and CO emissions were reduced by LEA firing. The effect of air adjustments to overfire nozzles was indeterminate with respect to CO emissions. For the second series of data, controlled particulate loading was also reduced by LEA firing. CO emissions are given only for baseline conditions; thus, no conclusions can be drawn.

Table 5-4. Secondary Pollutants, Stoker Boilers

Unit	Test No.	Test Load (10^3 lb/hr)	Excess O_2 (%)	NO (ppm)	HC (ppm)	CO (ppm)	Boiler Effic.	Part. Loading (lb/10^6 Btu) Unc/Con	Coll. Effic. (%)	Remarks
IB-6, SS	1	120	10.3	550	Not Measured	0	81	2.3/--	--	Baseline
	4	120	8.9	470		0	82	--/--	--	LEA
	11	120	9.0	494		0	--	--/--	--	Low NOx setup by putting max possible air through overfire nozzles
	12	120	11.8	475		0	--	--/--	--	Low NOx with side burners used for air distribution, staged short test
IB-7, SS	2	162	10.8	502		0	80	--/.4759	--	Baseline
	6	150	8.9	341		0	83	--/--	--	LEA
	13	150	11.0	270		0	--	--/--	--	High smoke, staged comb. short test
	14	147	11.5	333		0	--	--/.3445	--	High smoke, staged comb., longer test
	15	145	12.6	350		0	80	--/--	--	High smoke, staged comb., longer test
IB-11, SS	8	41	7.3	440		33	--	--/.84	--	Baseline
	9	41	5.8	324	25	24	--	--/1.55	--	LEA
IB-12, SS	6	63	7.8	456	16	122	--	--/1.24	--	Baseline
	10	63	5.9	377	23	71	--	--/1.24	--	LEA
IB-13, SS	134-2	82	6.2	314	Not Measured	24	87	3.1/--	--	Baseline
	135-2	82	5.2	221		22	88	2.0/--	--	LEA
	136-1	82	6.3	282		46	--	--/--	--	Air adjustment to overfire nozzle
	136-3	82	6.1	229		75	87	--/--	--	Air adjustment to overfire nozzle and air to gas burner register
	139-4	48	10.3	348		73	85	--/1.76	--	Low load, high to low O_2
	139-7	48	9.6	335		82	55	--/--	--	
	139-10	50	7.7	266		86	86	--/--	--	
	139-3	48	7.4	191		66	88	--/--	--	
Willmar 3, SS	10	72	9.5	338		262	--	--/.432	--	Baseline
	13	80	9.9	382		--	--	--/.675	--	High O_2

Continued

Table 5-4. Continued.

Unit	Test No.	Test Load (10^3 lb/hr)	Excess O_2 (%)	NO (ppm)	HC (ppm)	CO (ppm)	Boiler Effic.	Part. Loading (lb/10^6 Btu) Unc/Con	Coll. Effic. (%)	Remarks
MC	14	79	7.7	284		111	--	--/.387	--	LEA
	6A	109.5	7.7	333		378	--	--/--	--	Vary air adjustment - top row of overfire nozzle bias
	6D	109.5	7.3	355		237	--	--/--	--	Vary air adjustment - bias top row
	6E	109.5	7.2	313		352	--	--/--	--	Vary air adjustment - bias top row
	23	114.5	8.2	491		367	81.3	--/.74	--	Baseline, eastern coal
	33	109.8	6.6	375		--	81.5	--/.54	--	LEA, eastern coal
Fairmont, SS	3	48.9	9.3	320	--	38	78.0	1.44/.379	73.6	Baseline, eastern
MC	5	48.9	8.2	265	--	81	80.1	1.23/.294	76	LEA
	18	45.7	9.4	323	--	165	79.8	2.30/.484	78.9	Baseline, coal blend
	14	45.7	8.0	372	--	88	77.9	2.81/.411	85.4	LEA
St. Johns, SS	3	5.60	16.3	216	--	961	--	.846/--	--	Baseline
	5	5.72	15.1	199	277	95	--	.225/--	--	LEA
	18	7.75	14.3	344	130	226	--	1.287/--	--	Baseline
	16	7.98	13.4	264	71	116	--	.530/--	--	LEA
Boiler A, SS	4	182	6.3	497	--	219	80.5	--/.65	--	High O_2 Stansbury coal
MC, ESP	3	180	4.1	312	--	77	82.9	--/.58	--	Low O_2
	6	210	5.8	414	--	392	79.0	--/.95	--	High O_2 Stansbury coal
	5	216	4.1	355	--	536	81.6	--/.66	--	Low O_2
	28	242	3.9	408	--	1076	77.4	20.5/--	--	OFA (4" H_2O) Kemmerer coal
	29	252	3.8	398	--	480	79.2	15.4/--	--	OFA (9" H_2O)
IB-15, OS	165-1	104	9.5	164	41	39	76	--/.41	--	Baseline
	166-1	102	9.0	122	83	90	76	--/.375	--	Low O_2
	168-3	102	9.0	166	39	23	76	--/--	--	Stoker air adjustments
	168-2	107	8.5	150	53	36	--	--/--	--	Stoker air adjustments

SS - Spreader Stoker　MC - Mechanical Collector
OS - Overfed Stoker　ESP - Electrostatic Precipitator

Data for the Fairmont unit were divided for eastern coal and a coal blend with special interest placed on particulate loading and collection efficiency. For the eastern coal tested, particulate loading on a controlled and uncontrolled basis decreased with LEA firing. For the coal blend of eastern/western coal, uncontrolled particulate was higher than with the eastern coal. Collection efficiency of the cyclone dust collector increased with LEA for both eastern coal (73.6-76%) and for the coal blend (78.9-85.4%). The differences in cyclone efficiency between the eastern coal and coal blend may be attributed to particle sizing and particulate inlet loading.

St. Johns, the smallest of the spreader stokers tested (13,500 lb/hr steam capacity), was tested on both eastern and western coal. LEA firing reduced both particulate and CO emissions. CO emissions dropped from 961 to 95 ppm and particulate loading dropped from .846 to .225 lb/10^6 Btu. Similar trends for secondary pollutants were displayed for eastern coal.

Three sets of data are presented for Boiler A, representing one coal type for two loading conditions and a second coal type for one loading condition. For the first coal type (Stansbury, Wyoming) under two loading conditions, controlled particulate loading dropped with LEA firing. CO emissions decreased (219 to 77 ppm) with LEA at the lower load (180 k lb/hr) but increased (392 to 536 ppm) with LEA at the higher load (216 k lb/hr). A second coal type (Kimmerer, Wyoming) burned at loads of 242 and 252 k lb/hr, was tested at low OFA (4" H_2O) and high OFA (9" H_2O). CO emissions were significantly curtailed with high OFA from 1076 ppm CO to 480 ppm along with uncontrolled particulate loadings from 20.5 to 15.4 lb/10^6 Btu. It should be noted that the impact on NOx emissions with a high OFA was negligible.

The final stoker listed in the table is IB-15, an overfed unit. Controlled particulate loading was reduced with LEA from 0.41 to 0.37 lb/10^6 Btu but CO emissions (39-90 ppm) and HC emissions (41-83 ppm) increased with LEA. Stoker air adjustments, under load and O_2 conditions comparable to those of the LEA test enabled more burnout of CO and HC.

In summary, the finding is that secondary environmental impacts with LEA and/or stoker overfire air adjustments appear to be small. In fact, uncontrolled and/or controlled particulates decreased in every case with LEA. Low excess air through the grates reduces particle entrainment and particulate loading and increases residence time needed to burn the combustible. CO emissions increased in those cases where a very low excess O_2 was run (particularly at Willmar). Stoker overfire air adjustments usually have the effect of lowering CO but have a minor effect on NOx.

5.4 COST OF COMBUSTION MODIFICATIONS

Perhaps the most important consideration in the implementation of NOx control techniques from the viewpoint of the industrial boiler owner/operator is the cost associated with initial modifications of the boiler and costs associated with long term operation. Very few cost data for industrial sized units are available since NOx control has not been required on this type of boiler. The data that are available are generally taken from extrapolations of cost data for utility sized units that require NOx emission control.

Previous studies (Ref. 5-8, 5-9) have presented total cost data for NOx controls for coal-fired industrial boilers without a breakdown into the component costs. Cost data have also been presented as a function of boiler capacity (steam generation or heat input rate). However, the costs of several components are somewhat fixed and do not vary with the unit size. In this section, a list of the component costs and the factors that influence these costs will be made.

A summary of the major cost factors associated with the implementation of combustion modifications on a new or retrofit basis is presented in Table 5-5. These cost factors can be separated into the initial costs of implementation and the annual costs required to maintain and operate the respective systems. The initial costs are the costs associated with engineering implementation, the capital and installation costs of required equipment additions, and unit modification costs. Annual costs include (1) required equipment maintenance costs, (2) additional fuel costs, and (3) annualized capital costs.

As given in Table 5-5, low excess air (LEA) involves the initial costs of engineering implementation to identify minimum excess air levels and necessary auxiliary equipment such as an excess O_2 meter and perhaps a CO meter to provide combustion control to maintain these levels. LEA operation, unlike the other combustion modifications, has been implemented on numerous industrial boilers for increased efficiency. Hardware modifications are generally not necessary other than in extreme cases of severe air flow maldistribution. Annual costs include required maintenance of auxiliary equipment, a potential net cost credit for reduced fuel consumption and annualized capital costs.

Table 5-5. Summary of Combustion-Modification Cost Components

		Initial Costs			Annualized Costs		
Combustion Modification	Application	Engineering Implementation	Auxiliary Equipment	Unit Modifications	Maintenance	Fuel Costs	Capital Costs
Low Excess Air	Stoker and Pulverized	Combustion Consultant	Excess O_2 Analyzer Opacity Meter Improved Combustion Controls	None	Combustion Controls Burner/Stoker Grates	Credit	Investment Costs
Overfire Air	Stoker and Pulverized	Boiler Mfg/ Combustion Consultant	Excess O_2 Analyzer Opacity Meter Improved Combustion Controls	Overfire Air Ducts and Dampers	Combustion Controls and Instrumentation	--	Investment Costs
Burner Out of Service	Pulverized	Combustion Consultant	Excess O_2 Analyzer Opacity Meter Improved Combustion Controls	None	Combustion Controls and Instrumentation	--	Investment Costs

While overfire air (OFA) has not been implemented on any unit on a permanent basis, this technique has been included due to its success on larger units and the availability of estimated cost data. OFA includes all the items listed for LEA as well as modifications to the unit to provide OFA ports. Additional engineering evaluation on the part of the boiler manufacturer will be required during its design.

The major cost component for burners-out-of-service (BOOS) operation is in the engineering implementation (Ref. 5-10). Additional costs of combustion control and instrumentation are included. Note that BOOS operation can be applied only to pulverized coal-fired systems.

The following sections will discuss each of these cost components. A cost summary is provided at the end of the section along with estimated costs for several applications.

5.4.1 Engineering Implementation

Various degrees of expertise in coal-fired industrial boiler operation are necessary to evaluate and implement the combustion modifications discussed in this section. In some cases, plant personnel will have this expertise. Combustion consultants are generally required (1) for advanced combustion modifications, (2) in the cases where unit combustion problems are abnormally severe, or (3) where plant personnel lack the time, experience or equipment.

As discussed previously, implementation of LEA operations can generally be considered as a boiler tune-up. This includes an examination of the coal conditions, feed system operation and distribution, combustion controls, air damper positions and operation, grate and furnace conditions, etc. to assure that the unit is in peak operating condition. Required maintenance is performed as indicated by this inspection. Tests are conducted at several operating loads while varying the air/fuel level and distribution to establish the minimum practical excess air level with respect to fuel variability, load change conditions and furnace conditions. Adjustments are made to combustion controls as required to allow the unit to follow the desired excess O_2 versus load operation. These procedures can be performed by experienced plant personnel. Guidelines have been written to assist the owner/operator in implementing these operations (Ref. 5-11).

This evaluation will involve the use of in-stack measurements of excess O_2, opacity and NOx concentrations. While some plants are equipped with excess O_2 (or equivalent CO_2) analyzers and opacity meters, NOx emission instrumentation is generally available only through combustion consultants. LEA operation can be implemented without knowledge of the NOx emission levels; however, documentation of their levels is desirable from the standpoint of establishing emission reductions and meeting emission regulations which may be imposed.

The engineering effort required to implement LEA operation will vary with the size and complexity of the unit and the existing operating conditions. The cost of this service (including instrumentation) can range from \$5000 to \$10,000 for industrial sized units.

Most advanced combustion modifications using OFA and BOOS will require the services of a combustion consultant as well as input from the boiler manufacturer. OFA operation will include the LEA evaluation process discussed above along with determination of the optimal quantity of overfire air. This will involve the design and fabrication of ducting, dampers, air injection ports, etc. The correct placement of the ports so as to avoid any increase in total combustion air or disruption of heat release and absorption rates in the furnace is frequently a boiler engineering problem and should include the assessment of the boiler manufacturer. Following the unit modification, the optimal distribution between primary and secondary air flow and overfire air is determined with regard to unit efficiency and NOx emissions. The effects on secondary pollutants and carbon carryover are also considered.

Implementation of BOOS operation will also require combustion consultants. Determining the best pattern of burners to be taken out of service, accompanied by the proper air register settings and level of excess air to give the lowest nitric oxide emissions along with satisfactory combustion conditions, is usually a trial and error process. It requires accurate measurement of excess air and NOx emission along with engineering evaluation of combustion and heat release conditions for optimal results. The best burner pattern and air distribution cannot be determined a priori since even identical units can show different optimum conditions.

The engineering costs necessary to set up OFA and BOOS modes of operation are also difficult to estimate. Units equipped with OFA ports or burner arrangements suitable to BOOS operation will require much less effort than units that require modifications. The costs can range from $10,000 to $20,000 for industrial sized units.

5.4.2 Auxiliary Equipment

Operating the unit at the lowest practical excess air level is a primary part of each of the combustion modifications. Of primary importance in maintaining minimum excess O_2 levels is providing the operator with information on the excess air level in the operating unit. Experienced operators can generally tell when the unit is near minimum excess air levels. However, the fine tuning required for minimum NOx operation requires the use of excess O_2 analyzers and opacity meters. Improved combustion controls can allow the unit to operate at or reasonably near these levels automatically.

Some form of combustion control system is provided with even the smallest industrial sized boilers. Improvements in the operational control over the excess air level have frequently been implemented on new and existing units solely on the basis of improved boiler efficiency and not for NOx control purposes. In these cases, both reduced fuel use and reduced NOx emissions are achieved simultaneously.

Excess oxygen analyzers are generally used to determine the quantity of excess air in the furnace. The most modern design uses a zirconium oxide fuel cell located either in-stack or just outside the flue gas duct. Capital costs are approximately $2500 with an additional $1000 for installation. A conventional industrial boiler recorder for control room readout is $500. These units have been shown to be extremely reliable requiring only yearly calibration checks and cleanup on coal-fired systems (Ref. 5-12).

An opacity meter is customarily used with the excess oxygen analyzer for minimum excess air monitoring. Installed costs for these instruments can range from \$4000 for a single pass system to \$10,000 for a double pass unit. These units generally require only semi-annual maintenance.

Automatic control of the boiler excess air level can be achieved with more precise combustion control systems. In general, stoker-fired units with a large inventory of fuel in the furnace at any given time are controlled using the total air flow to regulate load and excess air levels and changes in the fuel flow to set the bulk load. Therefore, these units are not so responsive to load demands as pulverized coal-fired boilers. Variations in long term load are made by changing the fuel flow to the furnace by increasing the bed depth, rate of coal feed to stokers, ram rpm, etc. Stoker coal systems will generally trim the excess air level in the boiler by varying the flow of combustion air to the bed.

Modifications to existing combustor control systems include the use of an excess oxygen analyzer; an oxygen controller relates the excess oxygen level to load and an electric to pneumatic converter allows its incorporation into the pneumatic control system generally used on larger industrial boilers. Capital costs for such a system are approximately \$7000 with an extra \$2000 to \$4000 for calibration of the controller and installation (Ref. 5-12).

Complete combustion control systems can vary from \$25,000 to \$45,000 depending on the degree of sophistication (Ref. 5-12). The simplest control system used on coal-fired boilers is the parallel positioning type with operator trim. Air/fuel ratio is adjusted using an individual bias control on the fuel or air input. This system requires a combustion guide in the form of a controller governed by steam flow/air flow. This system is somewhat limited in that it does not compensate for changes in efficiency due to seasonal or fuel variations. The most complex control system uses a cross-limited metering system that limits the change in fuel flow to available air flow through a control logic circuit. The quantity of air flow is also tied to the existing fuel flow in that it must be equal to or greater than fuel flow. A common form is a pneumatic system using the steam pressure as the master controller. The air/fuel ratio is trimmed using a continuously monitored flue gas excess O_2 level.

5.5 *UNIT MODIFICATIONS*

The combustion modifications discussed in this report all involve the control of the fuel and air input to the furnace. This includes the size, composition and distribution of the coal feed, the combustion air conditions, and its distribution between the primary and secondary combustion zones. Industrial boilers in the size range of interest for this study generally have design features that use these parameters to control the combustion conditions in the furnace. The effectiveness of these for combustion efficiency and minimum air pollution emissions is limited by the age, size, and original intent of the owner/operator.

Several hardware modifications have been identified as potentially attractive for NOx emissions reduction. Among these are (1) installation of OFA ports, (2) modifications to dampers for improved distribution of combustion air either under the grate or at the burner face, and (3) modifications to coal feed ducting to allow optimum BOOS pattern operation.

Only limited implementation of low NOx modes has occurred on the industrial scale. However, some data are available from field research projects. Cost estimates are based on these tests as well as on extrapolation from the utility scale and on private communication with an owner who is currently building a stoker-fired boiler.

Estimates of the incremental costs for installation of OFA ducting on a new unit range from 0.1% to 4% of the cost of the boiler (Ref. 5-13, 5-14). An estimate of 1% would appear to be reasonable and corresponds well with industrial experience. Taking the total boiler cost for stoker-fired units to be $25 /pph (Ref. 5-15) would represent a range of cost estimates for unit modifications from $2500 to $100,000.

Modifications to existing units on a retrofit basis are even more difficult to make since the important parameters of fan capabilities, space, existing burner/grate arrangement and heat release rate vary between unit types. Costs for the installation of OFA ports, for example, are dependent on the tube spacing and wall construction. Based on utility boiler data (Ref. 5-1), incremental retrofit costs are approximately twice those for new units.

5.5.1 *Annual Maintenance Costs*

As discussed previously, the implementation of a combustion modification to effectively reduce NOx requires that the unit be maintained in good operating condition with boiler tune-ups to maintain peak combustion conditions. Estimates of the costs of this maintenance range from 2 to 9% of the initial capital investment (Ref. 5-16). A distinction between maintenance of items with and without moving parts has been made. Items with moving parts such as burners, fans and combustion controls require much more maintenance than items such as ducts or tube walls with no moving parts.

As discussed previously, modern excess O_2 analyzers require very little maintenance and calibration, usually on an annual or semi-annual basis. Cost estimates given by manufacturers are approximately 5% of the total installed costs.

5.5.2 *Incremental Fuel Costs*

Significant savings in fuel costs can be achieved through the use of LEA by increased operating efficiency. LEA operation has demonstrated increased efficiency by approximately 0.5% on pulverized units and 1.0% on stoker-fired units.

The net fuel costs associated with combustion modifications are dependent on the initial operating conditions of the units. A primary objective of all implementation programs is to maintain or increase unit operating efficiency. This can generally be accomplished on industrial units, as discussed in Section 5.2, if the final excess air level under modified combustion conditions is equal to or less than initial conditions.

The incremental fuel costs will also be dependent on the initial cost of the coal. Plants with several units receiving large shipments on a regular basis generally have a lower coal price than units relying on spot purchases. Coal prices are also affected by (1) the plant location, lower for plants near major coal fields or transportation networks, and (2) the coal conditions, i.e., low sulfur, ash and moisture content. The price of coal can vary by a factor of 2 to 3 depending on the coal quality (Ref. 5-15).

5.5.3 Investment Costs

This cost represents the annualized costs of the initial capital investment, usually expressed as a percentage of the total capital costs. Here, the capital costs are the sum of the hardware and unit modification costs and the engineering costs for implementation of the modification. Previous estimates of the annualized capital costs have ranged from 14-20% (Ref. 5-1). This annualized cost will vary with the individual economic situation of the company or industry involved due to variations in corporate interest rates and estimated lifetime of the capital investment for accounting purposes.

5.5.4 Incremental Cost Summary by Control Method

Table 5-6 presents the incremental costs of low excess air, overfire air and burners out of service for new boiler systems. These costs have been subdivided into the individual cost factors discussed in the previous sections. Cost estimates for three sizes, 50, 250 and 500 k lb/hr steam have been included. Note that estimates for the 50 k lb/hr steam class for BOOS operation have not been made since this would represent a stoker-fired unit to which this control method cannot be applied.

Estimates of the engineering implementation costs are based on extensive experience by KVB, Inc. These represent reasonable average costs but can vary depending on existing boiler conditions and the complexity of the control device. No cost variation with unit size has been estimated due to this uncertainty.

The auxiliary equipment costs have been taken to be the installed costs of excess O_2 analyzers, opacity meters and the hardware necessary for adaptation to existing control systems for all combustion modifications. These costs are essentially invariant with the size of the unit.

Unit modifications have been limited to installation of overfire air ports, taken to be 1% of the total installed cost of the boiler. Boiler costs have been taken to be \$20/pph for pulverized fired units (Ref. 5-18) and \$25/pph for stoker-fired units (Ref. 5-15). Retrofit application costs can be determined by doubling the unit modification costs.

Annual maintenance costs have been evaluated by the guideline proposed by Bartz (Ref. 5-10) and Bartok (Ref. 5-16). A distinction has been made for the systems employing moving and non-moving parts to allow a realistic estimate. The annual cost is evaluated as a function of the total capital cost according to the scale: systems with moving parts, 5.0%; systems without moving parts, 1.7%.

Incremental fuel costs (or in the case of LEA operation, fuel savings) result from a change in operating efficiency as compared to the initial operating conditions. For this analysis, nominal 0.5% and 1% efficiency improvements have been assumed for LEA operation in pulverized and stoker-fired units respectively. Corresponding load factors of 0.52 and 0.42 have been used together with a delivered coal price of $\$1.00/10^6$ Btu. This coal factor is low for some regions and could be as much as 2-3 times higher under certain circumstances.

The annual capital cost has been evaluated at 18% of the total investment cost.

Table 5-6. Combustion-Modification Cost Summary
(In 1978 Dollars)

Modification	Unit Size k lb steam/hr	Unit Type	Initial Costs (Dollars) Engineering Implementation	Auxiliary Equipment	Unit Modifications	Total	Annual Costs (Dollars) Maintenance	Fuel Costs	Capital Costs	Total	Percent of Total Boiler Costs
Low Excess Air	50	Stoker	7000	18000	(1)	25000	900	-2300	4500	3100	0.6
	250	Stoker	7000	18000	(1)	25000	900	-11500	4500	-6100	-
	500	Pulverizer	7000	18000	(1)	25000	900	-14350	4500	-8915	-
Overfire Air	50	Stoker	12000	18000	6000	36000	1000	0	6500	7500	1.5
	250	Stoker	12000	18000	27000	57000	1350	0	10300	11650	0.5
	500	Pulverizer	12000	18000	47000	77000	1700	0	13900	15600	0.3
Burner-out-of-Service	50	Stoker	NA	NA	NA	NA	NA	NA	NA	NA	NA
	250	Stoker	15000	18000	(1)	33000	900	0	5950	6850	0.2
	500	Pulverizer	15000	18000	(1)	33000	900	0	5950	6850	0.1

NA = Not appropriate

(1) Available equipment used

Table 5-6 also presents a total annual cost of the combustion modifications as a percent of the total annual cost of operating the unit, including annualized capital, fuel and maintenance costs (using the same assumptions as above).

Use of LEA will generally result in a cost saving while advanced staging procedures are estimated to represent a 0.1 to 1.5% increase in annual costs.

REFERENCES FOR SECTION 5

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Continued

REFERENCES FOR SECTION 5 (Continued)

5-17 Thompson, R. E., et al., *Assessment of the Potential for Energy Conservation Through Improved Industrial Boiler Efficiency*, FEA Contract C-04-50085-00 (October 1976).

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6 EASTERN/WESTERN COAL

6.1 WESTERN-COAL NOx EMISSIONS AS A FACTOR IN FUEL SWITCHING

Western subbituminous coals are attractive by comparison to eastern coals in terms of SOx and NOx emissions. However, the ash content and moisture content of western coals are significantly higher than for eastern coals, such that the conversion of a boiler from eastern to western coal for emissions reasons poses a number of potential problems. An assessment of the operational impact of coal switching for emissions control has been conducted (Ref. 6-1) for industrial boilers.

The primary factors to be considered when deciding to switch to western coal are: sulfur emissions, coal costs, transportation, SO_2 scrubber costs, and satisfactory operation of the boiler. NOx emissions would not be one of the main considerations in a decision to switch from eastern to western coal. In many regions of the country, the economics dictate the use of a local or regional coal. The recent western coal study by Maloney (Ref. 6-1) indicates a potential 12% decrease in NOx emissions as an average of all industrial boiler types upon switching from eastern bituminous coal to western subbituminous coal.

6.1.1 Properties of Western Subbituminous Coals

Emissions from coal-fired industrial boilers are determined both by coal properties and by boiler design. The compatibility of the coal with the boiler as well as the need for possible boiler modifications are important considerations in fuel switching and therefore the coal properties are variables of interest.

Western coal characteristics are those of a typical subbituminous coal: an ash-free higher heating value of 8,200 to 10,500 moist Btu/lb (19 to 25 MJ/kg) and a high moisture content of 20% to 30%. The ash content of most of these coals is less than 10% by weight. The western subbituminous coals exhibit high volatile to fixed carbon ratios, typically approaching a value of one. The western coals are typically non-coking, non-agglomerating, free burning coals with grindabilities that are a bit lower than for eastern coals.

6.2 COMPARISON OF NOx EMISSIONS FOR EASTERN AND WESTERN COALS

Nitric oxide emissions from both stokers and pulverized coal units have been measured for selected eastern and western coals. Fig. 6-1 presents nitric oxide emissions data as a function of excess O_2. The baseline data for both eastern and western coals are plotted for approximately constant loads selected for each unit tested.

NO emissions are shown to increase with O_2 for both eastern and western coals at all units. Marginal NO emission benefits were gained by switching from eastern to western coal for Alma 3 and Fairmont. It should be noted that a blend of 1/3 western, 2/3 eastern coal was used at Fairmont which may explain the negligible effect on NO emissions. Significant differences in NO emissions at Willmar may be explained by the fact that western coal (Montana) typically is burned at this unit. The eastern coal did not burn as well at this unit.

Operating at low excess O_2 with eastern coal lowered NOx emissions at all units. In general, western coal could be fired at lower excess air before combustible losses became a problem. This is due primarily to the higher ratio of volatile matter to fixed carbon content of the western coal which results in less solid carbon to be burned out in the post flame gases. The lower excess air requirements thus result in lower NO emissions.

Another factor that influences NO emissions is fuel bound nitrogen. Among all of the coal combinations used in evaluating the impacts of eastern/western coal on NOx production, the fuel nitrogen content of the western coals was generally less than that of

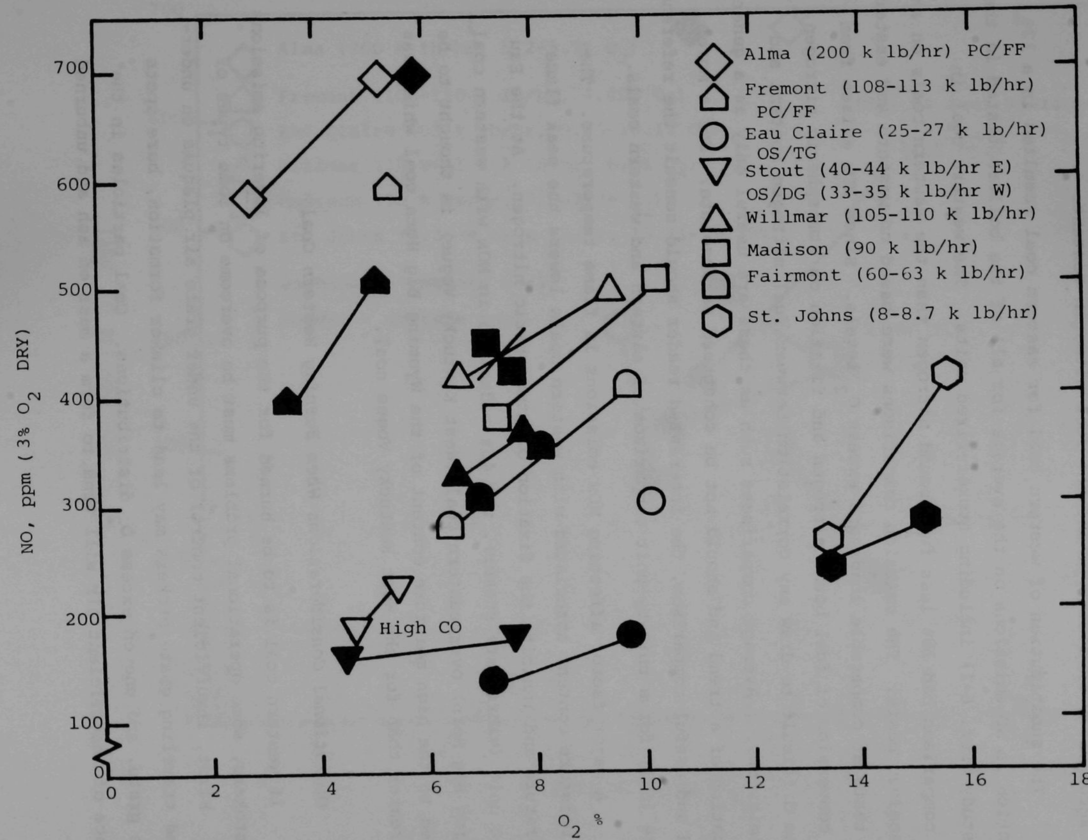

Fig. 6-1. NO versus O_2. Eastern (unshaded) versus western (shaded) coal.

the eastern coals. Fig. 6-2 is a plot of NO emissions as a function of fuel bound nitrogen (lb/10^6 Btu) for stokers and pulverized coal units.

The amount of NO converted depends primarily on the firing conditions and secondarily on coal type and the fuel nitrogen content.

The substitution of western coal for eastern coal resulted in a 12% reduction in NO emissions on the average for all of the boilers tested in the EPA study (Ref. 6-1) including stoker-fired units. The western coal in this comparison had 18% less fuel bound nitrogen than the eastern coals on an as-received basis. The emission comparisons were based on western and eastern coal tests at comparable loads and excess O_2 levels. Since NOx arises from both conversion of fuel bound nitrogen and fixation of atmospheric nitrogen, it was difficult to draw any correlation between fuel nitrogen content and NOx emissions. Average comparisons such as these are useful only as a general indication of a trend and should not be construed as absolute. For a more valid and useful comparison, the interested reader should consult the reference source (6-1) for a unit-by-unit comparison of eastern and western coals.

A major factor affecting NOx emissions is flame temperature. The high moisture content associated with western coals lowers the peak flame temperature and inhibits the fixation of atmospheric nitrogen. At the Eau Claire unit (vibrograte stoker), the 40% reduction in NOx with western coal (Wyoming Big Horn) over eastern coal (West Kentucky Vogue) is thought to be related to the high moisture content of the Wyoming Big Horn coal which was 50% greater than for the West Kentucky Vogue coal.

6.2.1 Operational Considerations When Burning Western Coal

If western coal is to be burned for the purpose of lowering emissions from stokers, some operational problems must be overcome on some types of units. First, insufficient control of the under grate air plenums on underfed and traveling grate stokers may lead to clinker formation, bare spots on the grate, and uneven excess O_2 distributions. Coal particles in the presence of insufficient air will tend to form a mass of ash and unburned

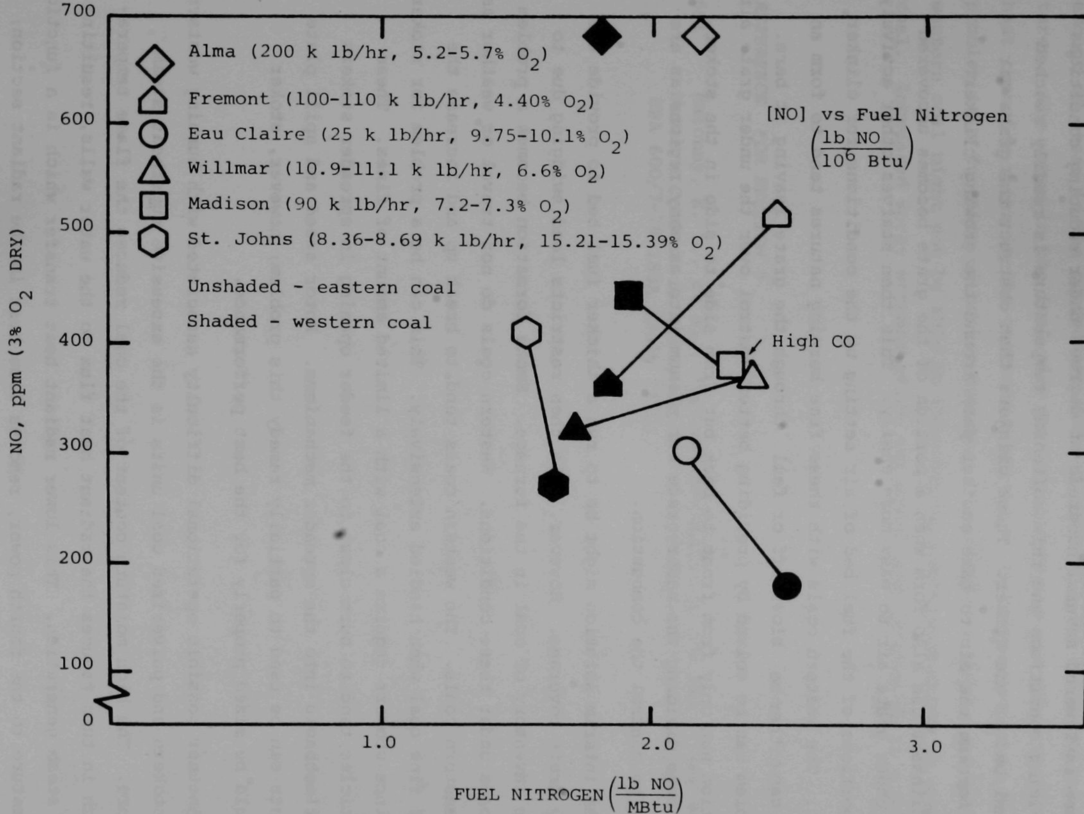

Fig. 6-2. Nitric oxide versus fuel nitrogen for eastern and western coals.

coal into what is termed a clinker. This happens because the ash softening temperature is lowered several hundreds of degrees under reducing conditions over oxidizing conditions and this softening temperature is readily reached in the fuel bed of the stoker. These clinkers then obstruct the grate air openings forcing the air to take another path around the growing clinker.

Clinkers can also form when a portion of the grate becomes uncovered allowing under grate air to pass more easily. This then starves other actively burning portions of the fuel bed of air setting up the conditions for clinker formation. The western coals with these free burning natures tend to form an ash that can either be blown off or fall through the grate leaving it bare. This problem can be solved by providing better control over the under grate air distribution not only from front to back but from side to side in the stoker. This may mean dividing the under grate air plenum into as many regions as are necessary to control the combustion.

An interim solution might be to run a thicker fuel bed to provide the necessary grate coverage. However, this then restricts load swinging due to the large inventory of coal in the furnace. Smoke formation becomes a problem at low loads under these conditions. Western coals do not travel or weather as well as eastern coals. The western coals tend to break up and increase the amount of fine coal when handled extensively. This can be a problem for stoker firing since stokers require a coal with a limited amount of fines. These fine particles tend to burn close to the feeder opening in spreader stokers causing flashbacks into the spreader mechanisms. Rotor speed and spill plate adjustments can be used to partially remedy this problem; however, stoker coal should be sized properly for the best performance.

Another possible operational difficulty associated with burning western coal in stokers and pulverized coal units is the excessive superheat steam temperature. The high moisture content of the coal reduces the flame temperature which in turn reduces the radiant heat flux to the water walls, resulting in lower steam generation. This lower radiant heat transfer which is a function of temperature to the fourth power, removes less heat in the radiant section;

however, the gas still contains a large enthalpy which then acts on a decreased amount of steam in the convective section, resulting in increased steam temperatures. The water in the fuel also results in greater gas flows which increase heat transfer rates in the convective section. The excessive steam temperature problem is a function of boiler design. For example, a boiler designed for western coal might not be able to make design steam temperature on eastern coal. Increased spray attemporation can solve this problem up to a point.

REFERENCE FOR SECTION 6

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7 *USEFULNESS OF CHEMICAL ADDITIVES*

The use of chemical additives to remedy problems encountered in boiler systems is a relatively recent development since most of the experience in its use has been gained within the last 15-20 years. Furthermore, most of this additive use has centered around oil fired boilers, while coal fired system experience is generally limited to the last five years, approximately. Among the problems which are purported to be solved by the various additives are:

- high temperature corrosion
- slagging
- combustion improvers (efficiency)
- fouling
- low temperature corrosion
- acid smut

In the past, due to the recent and limited experience of additive use in coal fired boilers, the major goals of research have been to exhibit and improve the effectiveness of additives as a control measure and to further refine the method of additive injection. As a result, very little is known about the effect on NOx or secondary pollutants of interest caused by the use of the additives. At this time, no published tests which have investigated additive use have examined their effect on NOx emission. Programs which are investigating the use of additives may yield concrete data in the near future.

The following subsections contain a discussion of the types of additives which are currently available for use in coal fired systems and their possible effects. The problems in boilers can be classified into the high temperature and low temperature problems.

7.1 HIGH-TEMPERATURE ADDITIVES

The problems encountered in the high temperature regions of a boiler are corrosion, slagging, and fouling of the radiant and convective sections. Incomplete combustion can also be a problem. Most of the additives offered for use in coal systems are intended to remedy the corrosion and deposit problems.

The occurrence of a slagging problem in a furnace will be dependent upon the ash fusion characteristics of the coal, furnace design, and the particular firing practice which is controlled by the boiler operator. The ash fusion temperature is controlled by the proportion of ash constituents. This ash composition governs the slagging potential of a particular coal. The constituents of the ash can be described as either acidic or basic in nature, and their cumulative effect is known to alter the melting point of the ash. The acid-to-base ratio $[(Fe_2O_3+CaO+MgO+Na_2O+K_2O)/(SiO_2+Al_2O_3+TiO_2)]$ is known to be correlated with the viscosity at the T_{250} slag temperature. The higher this ratio, the lower the T_{250} slag temperature will be (Ref. 7-2). Up to a point, the individual components of silica and Fe_2O_3 are also known to have an effect upon the T_{250} temperature of the ash. The lower the T_{250} or the fusion temperatures, the easier it is to melt the ash in the furnace. If the furnace is of the dry bottom variety, the formation of deposits of molten ash which solidify on the walls (slagging) reduces the heat transfer and can promote corrosion. For wet bottom units, liquid state ash removal is the designed operational mode, therefore exceeding ash fusion temperatures is promoted; however, the ash must not collect on the walls but must be allowed to flow to the bottom where it is tapped.

Fouling occurs from the collection of solid ash deposits on the high temperature convective section of the furnace. Again, the composition of the ash and the manner in which the particles strike the tube or metal surface determine the fouling potential of a particular coal/boiler combination. The fouling characteristics are related to the content of alkaline oxides of sodium and potassium (Na_2O and K_2O) and their interactions with the sulfur oxides produced from combustion. The result is the formation of the low melting compounds (Na_2SO_4 and K_2SO_4) (Ref. 7-3). These two compounds can then react with other components of the ash to form other low melting compounds of $Na_3Fe\ (SO_4)_3$, $NaFe(SO_4)_2$, $K_3F_2(SO_4)_3$ and $KFe(SO_4)_2$, which all have melting points between 1140 and 1290 °F (Ref. 7-4). These compounds will generally be molten in the hot gas stream and upon contacting a cool convection tube (800 °F) form a hard deposit. If the deposits cannot be removed by normal soot blowing operations, the deposits will continue to build and bridge the gas passages between the tubes. Furthermore, the existence of the deposits upon the tubes will produce an environment which allows corrosion to begin to attack the metal surfaces.

When a coal fired boiler is designed, allowances are made to accomodate the characteristics of the range of coals which are proposed to be burned in order to allow boiler operation with as few problems from slagging and fouling as possible. Additives may be a potential solution to a problem encountered by burning off design fuels.

High temperature additives are intended to change the fluxing characteristics of an ash so that it will not melt at a temperature such that slagging or fouling will be a problem. They may also change the physical characteristics of the ash such that if a deposit does form it can be easily removed by the soot blowing equipment.

In the past, additives were added directly to the coal prior to combustion. For example, in order to promote ash liquefaction in a wet bottom furnace, a fluxing agent such as limestone would be added at the rate of approximately 100 lb/ton coal; this added considerably to the particulate emission problem (Ref. 7-1). Current additive rates have been reduced to less than 1/20 of former rates, due to improvement in additive effectiveness.

The additives can be injected into the boiler in a number of different methods in order to handle particular problems. As mentioned, an early method of additive addition was to mix it with the coal. While this method of injection may be necessary for fluxing agents, it is generally least effective when treating slagging, fouling and corrosion problems, and only results in unnecessarily high additive requirements. The most effective method used today is to inject the additives directly on the troublesome portion of the furnace. In the case of slagging, this means just upstream of the slag build up or prior to the convective section for a fouling problem. The additives are injected either as an aspirated powder or in a liquid slurry. In order to further reduce additive requirements, injection periods can be sequenced to precede the soot blowing operation. This technique further increases the additive effectiveness.

The additives used for the control of slagging, fouling and corrosion are generally based upon the use of magnesium oxide (MgO), which chemically reacts with the low melting point, corrosive compounds to form higher melting point compounds. Alumina is also used, which reportedly alters the deposit structure and makes the ash deposits more friable. A friable ash deposit is more easily removed by soot blowers, preventing deposit buildup. Combination of the magnesium oxide and alumina have been reported to be more beneficial than when either is used alone (Refs. 7-3, 7-4).

The additives are either powdered solids or in slurries. Improvements in additive technology have shown that very fine powders are more effective than the coarser powders formerly used. The explanation given is that the surface area of the additive provides more reactivity. In liquid form, the additive compounds are usually water slurries of $Mg(OH)_2$. In the furnace, magnesia will dehydrate, given the proper time and temperature, to form the highly reactive MgO as a fine particulate (Refs. 7-7,7-8).

Additives for combustion improvement are also offered to mitigate problems of smoking by providing for more complete fuel burnout. These are generally described as combustion catalysts, and are injected or mixed prior to burning. MgO additives have also reportedly increased the carbon burnout by deposition of a more reflective coating on the furnace walls than is normal for slag or ash, which results in higher furnace temperatures (Ref. 7-3). Combustion catalysts can also be formulated from barium compounds.

7.2 LOW-TEMPERATURE ADDITIVES

The cold end problems which can be remedied by additive use are the related problems of corrosion and acid smut emissions. Cold end corrosion is differentiated from the high temperature variety not only in temperature range, but in the mechanism involved. Cold end corrosion occurs in the economizers and air preheaters where the flue gases might be exposed to low temperature surfaces.

Cold end corrosion happens when sulfuric acid is formed from the SO_3 and water in the flue gases. The proportion of SO_3 in the flue gases is only a small portion of the total sulfur oxides (SO_2 and SO_3), which are created during the combustion process, from the coal sulfur. This proportion of SO_3 to SO_2 can vary, and is known to be dependent upon the level of excess O_2 in the flue gas. While lowering excess O_2 to reduce SO_3 formation can be effective in oil fuel boilers, the excess O_2 levels required in coal firing usually preclude this possibility.

Since SO_3 cannot always be reduced to zero under normal circumstances, the temperature of the economizers' and air preheaters' metal surfaces must remain above the acid dewpoint to prevent condensation and subsequent corrosion. The presence of small quantities of SO_3 in the flue gas is known to raise the dewpoint, which then raises the allowable low temperature limit of the flue gas, before corrosion is experienced. Since this can limit the heat recovery from the economizer and air preheaters, a reduction in unit efficiency will be experienced.

Acid smut occurs from the condensation of acid upon the particulates in the flue gas which when exhausted from the stack may fall out from the air onto surrounding areas. Problems associated with acid smut are damage to vegetation and to painted surfaces. Again, the solution to an acid smut problem is to prevent excessive SO_3 formation and acid condensation.

Additives to prevent acid smut and corrosion are based upon the removal of SO_3 from the flue gas, which prevents acid formation. These additives are known to be effective, especially in oil fired units, where most of the experience to date has been gained. The chemical used is MgO, which combines with SO_3 to form $MgSO_4$. The additives are most effective when injected downstream of the combustion process. When using forms of MgO in the high temperature convective section, a side benefit is that the additive may reduce or eliminate problems further downstream. Alternately, the additive can be injected just upstream of the problem area.

In addition to the reduction of the acid dewpoint, other benefits which have been exhibited from additive use are: increased precipitator efficiency and reduced ash deposition in convective sections (Ref. 7-7). Precipitator performance was increased for two tests which showed a particulate emissions reduction of 19%. The increase in precipitator performance was explained by changes in fly ash resistivity due to SO_3 concentration and enhanced particle agglomeration. In a similar manner to the high temperature fouling problem, additive use lowers ash deposition on convective section tubes which can result in a reduced requirement for water washing. Savings in operating cost result from lower maintenance requirements (less frequent water washing or corrosion maintenance requirements) or from increases in boiler efficiency from the increased heat recovery allowed by changes in the acid dewpoint (Ref. 7-7).

7.3 EFFECT UPON NOx EMISSIONS

As mentioned previously, no tests have been performed which have shown the effect of the additive use upon NOx emissions. Since there is no expected reaction between MgO or other additives and NOx, there may be little or no effect. Possible effects upon NOx are most likely to result as a consequence of changes in boiler operation, especially near the combustion zone. It is well known that NOx formation is dependent upon the time/temperature history of the combustion gases, as well as the methods of combustion air addition. A possible effect may result from the use of a combustion improver, since a change in the method or rate of combustion could alter the closely tied NOx formation process. Since a combustion improver implies better or more rapid combustion, a possibility of a greater NOx emission exists. Of course, whether or not a change in NOx emissions does occur, it will be unknown until testing is performed with a particular additive.

One possible beneficial effect upon the NOx emission might be encountered when combustion improvement additives are used to reduce CO or smoke limitations and allow more flexibility in boiler operation. The greater operational flexibility could result in reduced NOx emission by allowing a greater degree of staging to be used before the smoke limit is reached. Normally, the two operational limits imposed by staged combustion are excessive CO or smoke. Since it is conceivable that additive use can reduce the CO or smoke limits, the greater degree of staging may allow greater NOx reductions than formerly possible. Whether this scheme is possible or how effective it may be on a coal-fired boiler is unknown, until testing is done to demonstrate the usefulness of this approach.

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8 ADVANCED CONCEPTS FOR NOx CONTROL FROM COAL-FIRED INDUSTRIAL BOILERS WITH RECOMMENDATIONS FOR FURTHER RD&D EFFORT

The conventional combustion of coal in the industrial sector is confined primarily to pulverized coal and stoker coal fired boilers. The advanced concepts for NOx control discussed below will be confined to these conventional coal firing systems and will not include a discussion of fluid bed coal combustion. Stoker boilers will be treated first followed by a discussion of advanced concepts for pulverized coal fired and cyclone fired boilers.

Recommendations for future research, development and/or demonstration projects will be included with the discussion of the individual firing type and summarized at the end of this section.

8.1 STOKER-FIRED BOILERS

NOx emissions from stoker units are relatively low by comparison to pulverized coal units but they can not be ignored in terms of potential impact with increased industrial coal use in some marginal air quality control regions. Characteristically, spreader stoker units have much higher NOx emissions than underfed designs but spreaders also are the most prevalent design. Almost all of the production of new industrial stoker units is of the spreader design and therefore the major effort in NOx control should be directed to these designs.

The options for NOx control on existing stoker units is very limited because there is a little latitude in modifying the combustion process without creating operational problems such as bed clinkering, grate damage, or loss of load. The most viable options identified for NOx control on existing spreader stokers were low excess air (LEA) operation and the use of overfire air ports (NOx ports). Low excess air operation requires very even distribution of combustion air to the bed and even sizing of the coal in the bed so that it burns uniformly. The grate design and air compartment configuration under the bed obviously has an impact on establishing these conditions. The major constraint in implementing LEA operations on stoker units is the possibility of forming fuel-rich pockets that clinker creating uneven burning rates and ultimately gross bed fuel/air maldistributions.

A second approach to NOx control in spreader stokers is to increase the air flow through the overfire air ports attempting to create a type of staged combustion where the fuel bed is operated with reduced excess air and the CO and smoke is burned out above the bed with additional air. However, in many existing stoker designs, the overfire air ports are very close to the bed surface and were primarily intended for CO burnout and not for NOx control. In spite of this limitation, significant reductions have been achieved in some cases with the use of overfire air admitted through an existing gas/oil burner. There is a definite need for a detailed evaluation and optimization of the design of overfire air ports as they affect NO, particulate, CO and HC emissions. Other parameters in NOx emissions are coal properties (sizing, volatility, and moisture content), grate design, grate cooling, etc.

Another NOx control technique that has yet to be proven effective is to reduce the heat release per unit of grate area. This has the effect of reducing combustion intensities and promotes slow fuel/air mixing which reduces fuel nitrogen conversion to NOx.

One suggested low NOx concept applicable to stoker firing is to run a clinkering, coking, substoichiometric bed followed by a controlled burn out section above this bed in which NOx formation could be reduced thorugh a combination of controlled staged air addition and heat removal. A clinker grinding system would be necessary in the bed region to facilitate ash removal and carbon burnout.

A system such as the substoichiometric fuel bed would be considered a form of advanced staged combustion which has shown some promise in controlling NOx emissions from P.C. fired boilers (discussed below).

Considerable fundamental research work is needed on mechanisms of NOx formation in fuel rich coal beds and the fate of organically bound fuel nitrogen upon substoichiometric combustion. Research is also needed in the second stage air addition region in order to optimize the process variables to achieve low NOx and maintain acceptable overall carbon utilization. Attention should also be given to any potential corrosion problem arising from the implementation of such reducing low NOx modes.

The concept of a cooled grate or fuel bed for NOx control may have some merit. Data from existing units indicate that the water cooled vibrograte stoker has lower NOx emissions than the other design types. This may be an artifact of the vibrating grate or it may be due to the water cooling of the grate. Grate cooling might lower peak bed temperatures to the point where areas of high NOx formation are reduced. Another unproven concept is that of using heat pipes implanted in the bed and attached to the grate. This would further lower bed temperatures near the top of the bed where the temperatures are the highest; the heat pipes would reject into the water cooled grate.

Research in the area of coal combustion in fuel beds should include such concepts as the grate heat removal systems discussed above. A laboratory study into this area would seem to be the most promising way to proceed.

8.2 PULVERIZED-COAL-FIRED BOILERS

NOx control from P.C. firing has taken several tacks in recent years. The most promising concept is that of advanced staged combustion presently under development at Babcock & Wilcox. This concept differs from the conventional staging in that the primary zone which is fuel-rich overall is physically separated from the second stage. Two distinct flames are burning in this system when it is operating properly. The primary flame operates at 70% stoichiometry while the second flame uses the balance of the air to bring the stoichiometry up to 110%. Heat removal in both stages is important to control flame temperatures and furnace exit gas temperatures. Directional control is required on the tertiary air admission vanes in the second stage to provide the proper degree of fuel air mixing necessary for flame stability, carbon burnout and low NOx emissions.

Tests at a scale of four million Btu/hr at B&W have produced emissions of less than 100 ppm in the stack at three percent excess O_2. Work is in progress to scale this combustor up to the 50 million Btu/hr size.

Another approach to low NOx emissions from coal fired boilers has been to build a multi-register burner that will provide the proper fuel/air mixing flame properties. The characteristic of these flames for low NOx emission is usually long distributed mixing flames. The slowed mixing of the fuel and secondary air gives rise to a staging process along the flame length. The goal of the low NOx burner designs is to aerodynamically control this mixing process in the near and intermediate burner flow field. This control is not easily achieved without separate mechanical containments for each stage, or physically separated second stage air admission.

Another promising area for NOx control is in the use of burner modifications. KVB has pioneered the use of flame splitters on pulverized coal-fired boilers to achieve a low NOx emission mode. These "fingers" or aerodynamic splitters divide the cone of a normal primary coal and air mixture into four separate regions. The theory behind the practice is similar to all staging attempts (that is, to create local fuel-rich environments in which the bulk of the coal particles will devolatilize and then control the rate of the fuel air mixing downstream of this volatile burning region). KVB has had good success using such splitter burners on the utility scale. The application of this concept to the industrial pulverized coal-fired sector could proceed along the same route as the utility boiler.

The most promising areas for further research and development work appear to be in understanding the NOx reduction reactions that occur in the second stage flame of the advanced staged combustion process. From the present vantage point this separated furnace concept appears to have the most application to new and existing units. This system also holds the most promise for low NOx combustion of a wide range of coal types from lignite to Pittsburgh seam No. 8.

Laboratory scale studies on the second stage NOx reduction reaction should proceed simultaneously with the pilot scale demonstration projects. There is also the important question of scaling the process to the commercial size.

8.3 CYCLONE-FIRED INDUSTRIAL BOILERS

Cyclone boilers as a class have not received much research attention in the past because their very high NOx emission levels seemed insurmountable. Some work has been done with low excess air and some limited attempts have been made at staged combustion. The cyclone combustor, however, is an attractive way to burn troublesome coals and would be a viable market item if the NOx emissions could be reduced.

The cyclone furnace can probably be made to operate in much the same manner as the divided chamber advanced staged combustor under development for pulverized coal. In this configuration the cyclone would constitute the primary furnace which would run at 70% stoichiometry. The gases exiting the cyclone would be burned in the second stage with the controlled air addition. The application of the advanced staging concept to cyclone furnaces seems feasible since data from the divided chamber pulverized coal furnace have shown that the stack NOx concentrations are relatively insensitive to the primary furnace exit NOx concentrations. That is, the primary furnace can have high concentrations of NOx and still be able to maintain the low stack concentrations.

Recommended work in this area should be done at the laboratory scale. Experiments using the cyclone as the primary furnace could follow the direction taken for the advanced staged pulverized coal concept. A field demonstration would follow the successful laboratory program.

8.4 RECOMMENDATIONS FOR RD&D PROJECTS

The programs summarized in this section have been discussed in the previous sections.

Stoker-Fired Boilers

1. Investigate and optimize the design and use of overfire air ports
2. Reduce the heat release rate per unit of grate area

3. Develop clinkering bed concept
4. Conduct fundamental research program on NOx formation mechanisms in fuel-rich coal beds
5. Investigate controlled bed temperatures through cooled grates or heat pipes implanted in the fuel bed

Pulverized-Coal-Fired Boilers

1. Apply advanced staged combustion burner to industrial sized units
2. Develop multi-register burners for close control of the air/fuel mixing patterns
3. Apply flame splitters to modify existing burner configurations
4. Conduct fundamental research into the mechanisms of NOx formation during the second stages of the combustion process

Cyclone-Fired Industrial Boilers

1. Apply advanced staged combustion concepts to existing burner designs

9 UNRESOLVED ISSUES AND FUTURE INFORMATION NEEDS

During the course of preparing this study, several limitations in available data were identified that prevented a complete assessment in some topic areas. These deficiencies have been discussed in detail in the previous sections. Future information needs to resolve these issues are summarized in this section.

9.1 BASELINE NOx-EMISSION LEVELS FROM COAL-FIRED INDUSTRIAL BOILERS (Section 3)

Limited baseline NOx-emissions data were available for most designs of industrial boilers. With the possible exceptions of tangentially fired, single-wall-fired, and spreader-stoker units, additional as-found NOx-emission data are necessary to quantify emissions. This is especially true for cyclone and horizontally opposed units, where data from only one industrial-sized unit were available. Additional data on spreader-stoker units are warranted by their high coal use and the fact that nearly all new stoker units are of this design.

Further test programs to determine as-fired emission levels should include operation at reduced and variable load conditions, which is more characteristic of normal operation. The data available were limited primarily to test conditions at or near full load.

9.2 COMBUSTION MODIFICATIONS TO REDUCE NOx EMISSIONS

NOx-emissions data under low-excess-air (LEA) operation appear to be adequate to characterize the reduction potential for all types of units. The reduction potentials for industrial-sized pulverized-coal-fired units are further reinforced by similar data on utility-sized units. The primary research needs for LEA firing involved the operational considerations of slagging, fouling, corrosion, clinker formation, etc.

Data demonstrating the effectiveness of staged combustion, on the other hand, are almost non-existent. This is especially true for stoker-fired units, which will require test programs using specially designed overfire-air ports for NOx control. (The design considerations for such a system are discussed in Section 5.) The success of simulated tests using auxiliary burners certainly warrants such an evaluation. Staged combustion on pulverized-coal-fired systems was limited to simulated burner-out-of-service (BOOS) evaluations. These tests have shown favorable reduction potentials. Evaluation of additional BOOS operation on industrial-sized units, however, should be limited to units that have furnace configurations conducive to such procedures.

No data from pulverized-coal-fired units equipped with overfire-air ports were available. Staged combustion using these techniques should be actively pursued, as it could demonstrate the substantial NOx reduction demonstrated on utility-sized units.

Only limited data on the influence of burner adjustments were reported. Again, the significant NO-reduction potentials warrant additional evaluation. Modifications to burner configuration (as discussed in Section 8) could have similar results.

9.3 OPERATIONAL CONSIDERATIONS

Perhaps the most significant lack of information was in the area of various operational considerations associated with NOx combustion modifications. No data were available on the long-term effects on corrosion, maintenance, and unit reliability. Evaluation of these criteria is critical to the eventual acceptance of combustion modifications for NOx control by the industrial-boiler user/operator. The long-term effects of low-excess-air operation on stoker units are especially important, because of the formation of clinkers and grate overheating.

Additional information is also necessary to assist in the design of burners, air-mixing patterns, and grate configurations for optimum operation with minimum NOx emissions.

Important factors related to energy use and secondary pollutants also warrant further evaluation. Existing data, while demonstrating that the combustion modifications have little if any detrimental effect, are incomplete. Additional data on carbon carryover are needed, especially.

The cost associated with combustion-modification techniques must also be resolved. While the limited data also show this to be relatively insignificant in relation to total boiler-operation costs, the influence of this parameter on the eventual use of these techniques cannot be overemphasized. Several case studies should be developed.

9.4 EASTERN/WESTERN COAL

Expansion of these data to include various coal parameters such as fuel-nitrogen content, ash constituents, fuel preparation, etc. is also warranted. Few data on these factors were available. With the increasing importance of western coal as a replacement for traditional eastern coal supplies, additional studies of the influences of coal properties are certainly needed.

9.5 USEFULNESS OF CHEMICAL ADDITIVES

No information on the effects of additives on NOx emissions was available. Such studies are needed not so much for clarifying the possible influence on NOx emissions, but as a means of alleviating operational problems such as slagging, fouling, or corrosion that may result from combustion-modification techniques.

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